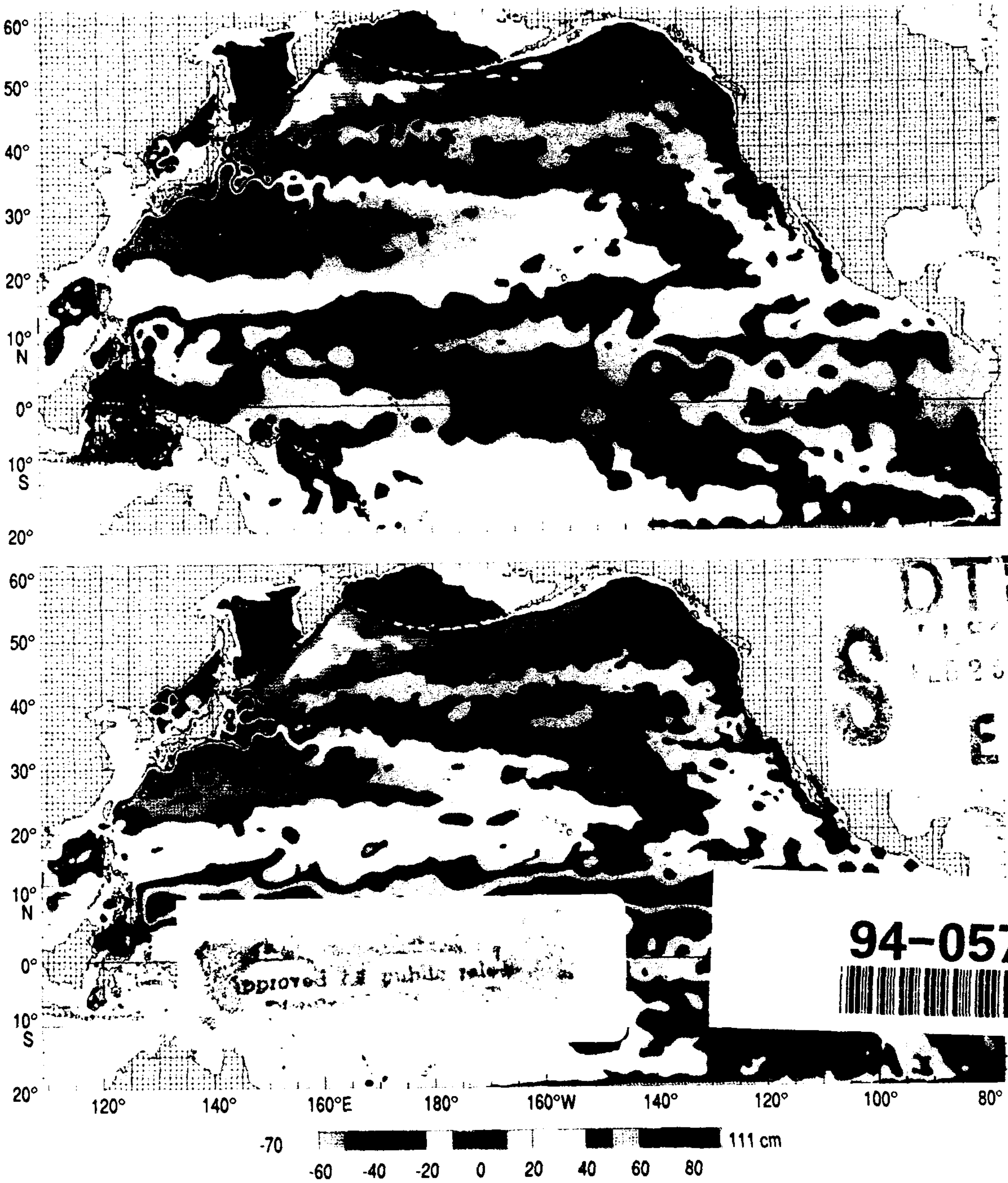
(12)

VOL 5, NO. 1

OCEANOGRAPHY

PUBLISHED BY THE OCEANOGRAPHY SOCIETY



Ocean Modeling and Prediction • Western Tropical Atlantic

1992 • VOLUME 5 • NUMBER 1

OCEANOGRAPHY

SERVING OCEAN SCIENCE AND ITS APPLICATIONS

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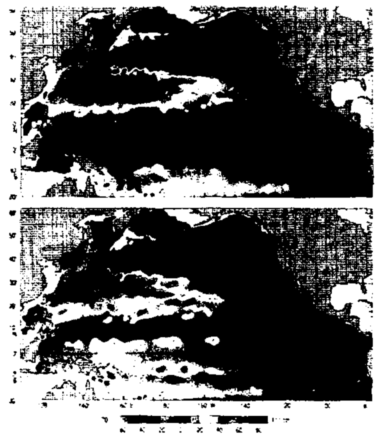
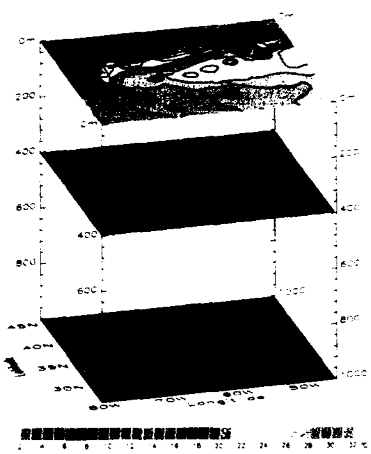


FRONT COVER
Sea-surface height simulated by a 1/8°, 6-layer Pacific ocean model for (top) 17 December 1986 and (bottom) 16 December 1989. The model has realistic bottom topography. Color bar is in centimeters and the extreme values labeled on the color bar are the extremes over the two dates. Meandering contours and eddies are ubiquitous, and strong interannual differences are evident. The simulation was performed on the Cray Y-MP8/8128 at the Naval Oceanographic Office, Stennis Space Center, MS, as part of the Naval Ocean Modeling Program.



BACK COVER
Temperature at 0, 400, and 1,000 m depth in the Gulf Stream region from Version 3.0 of the Optimum Thermal Interpolation System (OTIS) model on 26 July 1991. The contour interval is 1°C, and the color bar indicates temperature ranges in °C.

Oceanography (ISSN 1042-8275) is published by The Oceanography Society, 1701 K Street, N.W., #300, Washington, D.C., 20006-1509.

WIOP

IN EARLY APRIL, The Oceanography Society (TOS) sponsored an imaginary meeting focused on the exciting topic of "Words in Our Publications." The polarization of this topic quickly became obvious when two organizations unfurled their banners: 1) ACPJA (Action Committee for Proliferation of Jargon and Acronyms) and 2) The Subset of Scholarly Scientists Who Choose to Exercise the English Language for Technical Writing in a Fashion that is Clear, Correct, and Understandable by the Largest Possible Segment of Our Community. As the Director of Publications, I had the responsibility to moderate the proceedings.

First, the CEO of ACPJA spoke to the meeting attendees. He thanked the DOP of TOS for organizing WIOP. However, I soon realized that I was SOL, when he turned attention to the upcoming 5(1) of *Oceanography*. He attacked the wall clock hours that his colleagues had wasted transitioning their text to meet my silly requests. He felt that they had assimilated my quasi-operational data stream, but nowcasting from his own paper to others in the issue indicated a skill no better than persistence. True progress required PCV (precise, concise vocabulary), he bellowed as one-half of the audience rose applauding and the other half sat dumbfounded.

Next, the second vice president-elect for the Subset of Scholarly Scientists Who Choose to Exercise the English Language for Technical Writing in a Fashion that it is Clear, Correct, and Understandable by the Largest Possible Segment of Our Community was introduced. She thanked the Director of Publications for The Oceanography Society for organizing this imaginary meeting to address "Words in Our Publications." Once again I squirmed in my seat as she addressed the special issue of *Oceanography* focused on Ocean Prediction and Modeling. Fortunately, her time expired before she could get started. Otherwise she would have expressed her message that the use of specialized and abbreviated vocabulary restricted the understanding of written documents to the privileged few possessing the magic code book.

With trepidation, I rose to give some concluding remarks. Despite noise on both sides of me, I tried to look straight ahead and explain my opinion. The vocabulary used in a written document should vary depending on the purpose and audience of that document. If the purpose is to expose a specialized field and the advances of that field to a larger scientific audience, then much of the unique nomenclature and vocabulary must be exposed as well. However, highly specialized words and jargon cannot be allowed to render the written document incomprehensible to the larger scientific audience (LSA).

So ended our imaginary meeting, as banners were brought down and folded. And so starts this special issue of *Oceanography*. I enthusiastically thank Bob Peloquin and the authors for responding to my suggestions. And I congratulate the LSA for learning the Glossary of Acronyms before turning the page.

—Chuck Nittrouer

Letters are welcome regarding articles, the Quarterdeck editorial, or other matters relevant to *Oceanography*. We have received several, and these will be published in the next issue.

OCEANOGRAPHY SOCIETY 1988

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GLOSSARY OF ACRONYMS FOR FEATURE ARTICLES IN THIS ISSUE

ADCP	Acoustic Doppler Current Profiler
AGCM	Atmospheric Global Circulation Model
AIDJEX	Arctic Ice Dynamics Joint Experiment
ATHENA	Acquisition de donnees de Topographie de surface et d'Hydrologie dans l'Est Nord Atlantique
AVHRR	Advanced Very High Resolution Radiometer
AXBT	Airborne Expendable Bathythermograph
CME	Community Modeling Experiment
CNRI	Corporation for National Research Initiatives
COAP	Centre for Ocean Analysis and Prediction
CPU	Central Processing Unit
CTD	Conductivity Temperature Depth (sensor)
DAMEE	Data Assimilation and Model Evaluation Experiments
DAMOD	Data Management Module
DARPA	Defense Advanced Research Projects Agency
DART	Data Assimilation Research and Transition
DMSP	Defense Meteorological Satellite Program
DOE	Department of Energy
ECMOP	Experimental Center for Mesoscale Ocean Prediction
ECMWF	European Centre for Medium-range Weather Forecasts
EKF	Extended Kalman Filter
EMS	ECMOP Modular System
ERM	Exact Repeat Mission
EUC	Equatorial Undercurrent
FNOC	Fleet Numerical Oceanography Center
GCM	General Circulation Model
GDEM	Generalized Digital Environmental Model
GEOSAT	Geodetic Earth Orbiting Satellite
GEM	Goddard Earth Model
GMT	Greenwich Mean Time
GOM	Gulf of Mexico
GSOWM	Global Spectral Ocean Wave Model
GUI	Graphical User Interface
HE	Halmahera Eddy
IFD	Implicit Finite Difference
INO	Institute for Naval Oceanography
IR	Infrared Radiometers
ITCZ	Intertropical Convergence Zone
JIC	Joint Ice Center
JGOFS	Joint Global Ocean Flux Study
LEWEX	Labrador Extreme Waves Experiment
MCSST	Multi-Channel Sea-Surface Temperature
MIMD	Multiple-Instruction/Multiple-Data
MIZEX	Marginal Ice Zone Experiment
MODE	Mid-Ocean Dynamics Experiment
NASA	National Aeronautics and Space Administration
NAVOCEANO	Naval Oceanographic Office
NCAR	National Center for Atmospheric Research
NEC	North Equatorial Current
NECC	North Equatorial Countercurrent
NEONS	Naval Environmental Operational Nowcast System
NMC	National Meteorological Center
NOAA	National Oceanic and Atmospheric Administration
NOAMP	North Atlantic Monitoring Program
NOARL	Naval Oceanographic and Atmospheric Research Laboratory
NOGAPS	Navy Operational Global Atmospheric Prediction System
NOGUFS	Naval Operational Gulf Stream Forecast System
NOMP	Navy Ocean Modeling and Prediction
NORAPS	Navy Operational Regional Atmospheric Prediction System
NORDA	Naval Ocean Research and Development Activity
NRL	Naval Research Laboratory
NSF	National Science Foundation
NUSC	Naval Underwater Systems Center
NWP	Numerical Weather Prediction
OGCM	Oceanic Global Circulation Model
OI	Optimal Interpolation
OLS	Optical Line Scanner
ONR	Office of Naval Research
ONT	Office of Naval Technology
OPTEST	Operational Test
OPTOMA	Ocean Prediction Through Observation, Modeling and Analysis
OPW86	Ocean Prediction Workshop in 1986
OTIS	Optimal Thermal Interpolation System
PBL	Planetary Boundary Layer
PE	Primitive Equation
PEDAM	Primitive Equation Data Assimilating Model
PIPS	Polar Ice Prediction System
POLYMODE	Polygon (Russian for moored array) Mid-Ocean Dynamics Experiment
POPS	Primary Ocean Prediction System
PROTEMS	Prototype ECMOP Modular System
QG	Quasigeostrophic
R & D	Research and Development
REX	Regional Energetics Experiment
RMS	Root-Mean-Square
RPIPS-B	Regional Polar Ice Prediction System—Barents Sea
RPIPS-G	Regional Polar Ice Prediction System—Greenland Sea
SBL	Surface Boundary Layer
SEC	South Equatorial Current
SIMD	Single-Instruction/Multiple-Data
SSH	Sea-Surface Height
SSMI	Special Sensor Microwave Imager
SST	Sea-Surface Temperature
SPEM	Semi-spectral Primitive Equation Model
STACS	Subtropical Atlantic Climate Studies
SYNOP	Synoptic Ocean Prediction
TESS	Tactical Environmental Support System
TKE	Turbulent Kinetic Energy
TOPS	Thermodynamic Oceanographic Prediction System
TROPE	Trial Ocean Prediction Experiment
UCAR	University Corporation for Atmospheric Research
VERMOD	Verification Module
VISMOD	Visualization Module
WAM	Wave Model
WOCE	World Ocean Circulation Experiment
XBT	Expendable Bathythermograph

FEATURE

THE NAVY OCEAN MODELING AND PREDICTION PROGRAM

FROM RESEARCH TO OPERATIONS: AN OVERVIEW

By Robert A. Peloquin

"Develop a Global Ocean forecasting capability. . . ."
Rear Admiral J.R. Seesholtz, 1986

. . . to produce three-dimensional environmental data fields for assessing and predicting the performance of operational systems . . .

THE QUOTE, by the Oceanographer of the Navy, accurately conveys the theme of the articles that follow. Although the ultimate goal of this new capability is to meet Navy needs, there will be beneficial outflow to the marine community. The motivation for this development was originated in 1984 by John Lehman, then Secretary of the Navy, through his "Policy on Oceanography," which identified a number of initiatives ranging from scientific program enhancements to organizational changes. At the time, ocean modeling know-how and computer technology had progressed sufficiently to warrant a sizeable investment to achieve this forecasting capability.

The Oceanographer of the Navy and the Chief of Naval Research sponsored a comprehensive Ocean Prediction Workshop in 1986 (OPW86) to review progress in ocean modeling and to identify scientific and technological opportunities that facilitate the development of ocean prediction capabilities. The Oceanographer also initiated a supercomputer acquisition effort. The first of two Cray YMP computers is presently installed at the Naval Oceanographic Office (NAVOCEANO), Bay St. Louis, Mississippi, and through an agreement with the Chief of Naval Research is being used for model development as well as operational predictions. The second will be installed at the Fleet Numerical Oceanography Center (FNOC), Monterey, California, in 1992. In addition, the Navy is installing highly capable computer systems for environmental prediction aboard key ships and planes. Computer generated atmospheric and oceanic data fields transmitted from shore sites will be combined with measurements received from satellites, and observed on-site (Fig. 1). The objective is to produce three-dimensional environmental data fields for assessing and predicting the performance of operational systems (sonar, radar, weapons systems, etc.). Numerical products generated by FNOC and NAVOCEANO are transmitted to the Regional Ocean Centers and to Fleet Units. The Regional Ocean Centers, distributed globally, produce special-interest tactical products for specific areas.

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Navy Ocean Modeling and Prediction Program (NOMP)

NOMP was established by the Director of the Office of Naval Research jointly with the Director of the Office of Naval Technology and with the Technical Director to the Oceanographer of the Navy, as a mechanism to expedite models through research to an operational stage. The progression of this model development, as depicted in Figure 2, involves the assessment of model performance in the prototype development stage and extensive testing in both off-line (simulated operational conditions) and on-line operational environments before acceptance for use. FNOC is responsible for the final test and operational implementation of large-scale models (global, basin, and regional, including the Arctic), and NAVOCEANO is assigned the semi-enclosed sea and coastal models. Models destined for Fleet Units (Regional Ocean Centers, ships, etc.) are tested by the Oceanographic Office and upon acceptance for "Navy use" are provided to appropriate Naval activities. For instance, a shipboard model is presently being interfaced with acoustic models to predict the performance of anti-submarine sonar systems aboard aircraft carriers and cruisers.

The recommendations that emerged from OPW86 greatly influenced the structure and the evolution of Navy ocean modeling to date. The "Global Capability" involves a hierarchy of mod-

els of differing grid size, ranging from global to regional (including shipboard) scale (Fig. 3). As conceived, the larger scale provides internal fields and boundary conditions to the smaller scale models. For example, a global $\frac{1}{2}°$ ocean circulation model (now running operationally at FNOC) will provide boundary conditions and internal fields for a $\frac{1}{10}°$ regional model of the Northwest Atlantic (presently being evaluated for operational use).

Implicit to a forecast system is the ability to continuously assimilate data into a circulation or ocean prediction model. A forecast model of the Northwest Atlantic is expected in 1992, and a global capability will be available in 1996. The models will be eddy resolving, i.e., they will provide accurate depictions of fronts and eddies, including the subsurface density structure associated with these. The importance of this capability is illustrated in Figures 4 and 5, using model output data of the Gulf Stream region. Acoustic propagation loss for a 500-Hz signal was computed using oceanographic predictions obtained from a combination of the Harvard dynamic model (see Robinson, 1992, this issue) and the Navy Optimal Thermal Interpolation System (OTIS). The propagation-loss calculations were performed using the parabolic-equation formulation for two-dimensional propagation in vertical planes, chosen radially at 2° intervals. Propagation-loss, in decibels relative to one micropascal, is presented on a horizontal plane selected at 100 meters below the surface. Red and light yellow are synonymous with low loss, and indigo with high loss. A submarine target outside a red or yellow region probably would not be detected.

The dark wavy line through the center of Figures 4 and 5 represents the northern boundary of the Gulf Stream. The concentric circles are eddies that have pinched off from Gulf Stream meanders. To the north of the Gulf Stream are warm-core eddies, and to the south are cold-core eddies. Accurate knowledge about the location of these thermal features is of tactical significance for target detection and the deployment of forces. In Figure 4, the receiver is located within a warm-core eddy (at the center of the yellow patch), and a solid and widespread detection zone is prevalent in the immediate vicinity of the eddy. The receiver in Figure 5 is located 35 miles to the east, outside the eddy. Red bands indicative of acoustic-ray-path convergence zones present a significantly different picture. Noteworthy shadow zones, having Naval tactical implications, are created by the nearby eddy and along some sections of the Stream itself. These zones result from the refraction of acoustic rays as they pass through abrupt changes in the density structure. Ships conducting anti-submarine operations in similar regions would require constant updating about these features, to assure the proper positioning to provide optimum detection conditions.

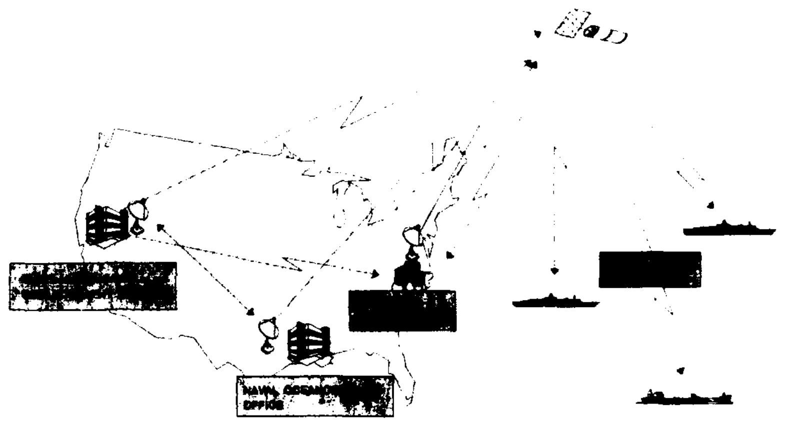

Fig. 1: Data and information flow from shore sites (large-scale computers) to fleet units at sea and ashore.

Although the program is ambitious, it is nevertheless attainable. Academic involvement is viewed as an essential element to success. As a result, the research base of the ocean-modeling program is closely tied to the Office of Naval Research, Research Programs Department, which supports university research. The Institute for Naval Oceanography, funded through the Navy Ocean Modeling and Prediction Program, has established a project for the comparative assessment of forecast models that have been developed through university research. This effort is expected to formulate recommendations for future model development. In this sense, the Institute provides a bridge between academic research and Navy applications. The Naval Research Laboratory (NRL) also is participating in this effort.

. . . the ability to continuously assimilate data into a circulation or ocean prediction model.

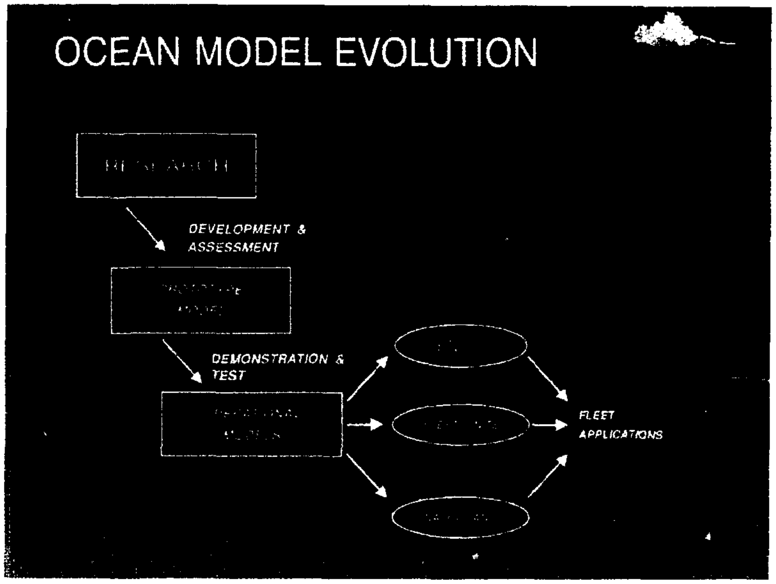

Fig. 2: Research and development process for ocean models.

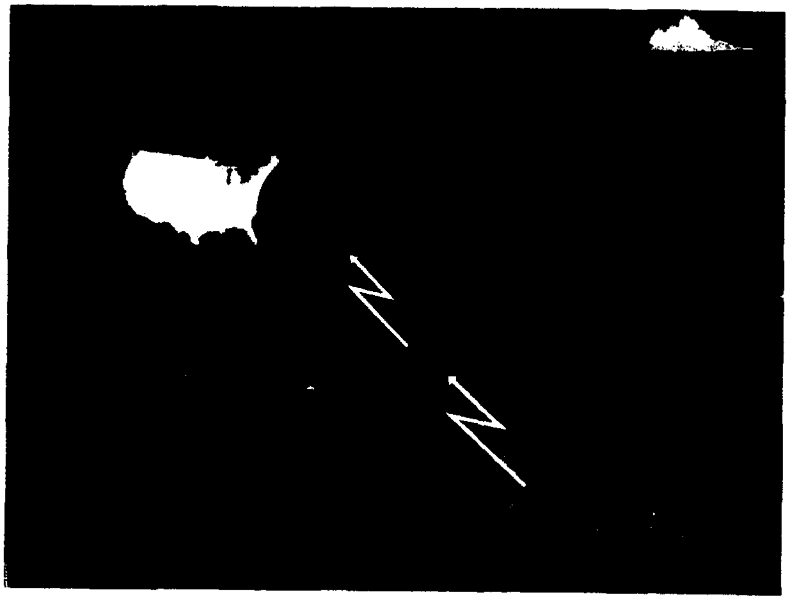

Fig. 3: Model development, i.e., global- to basin- to regional-scale.

. . . the program has clearly emphasized the large-scale models, i.e., global, basin, and regional.

NRL is involved in another essential element, namely, the establishment of prototype models. This assures compatibility within the Navy operational environment and the evaluation of the models using the best available data sets in an off-line quasi-operational mode. To achieve this objective, NRL works closely with NAVOCEANO and FNOC to assure the smooth transition of prototype models to operational use. With regard to data, the daily and even weekly volume of oceanographic data available for model input is very sparse. For that reason, the accuracy of oceanographic forecasts are expected to be dependent on the methods used for the assimilation of available data into the models.

A Description of the Modeling and Prediction Capabilities

NOMP was established to assure full consideration of modeling research and to accelerate the establishment of research results as operational models. The articles appearing in this issue of *Oceanography* were specifically selected to convey the scientific and technical content of the program.

The model development within the program has clearly emphasized the large-scale models, i.e., global, basin, and regional. The Navy is committed to the implementation of an operational forecast system by 1996. Hurlburt *et al.* (1992, this issue) discuss some aspects of the global effort in their large-scale modeling paper. One highlight of the article is the comparison of geodetic Earth-orbiting satellite (GEOSAT) sea-surface-height measurements with sea-surface heights computed using the $\frac{1}{2}°$ resolution model now running at FNOC. This work suggests that the assimilation of satellite measurements of sea-surface height into global models may soon be feasible. Equally sig-

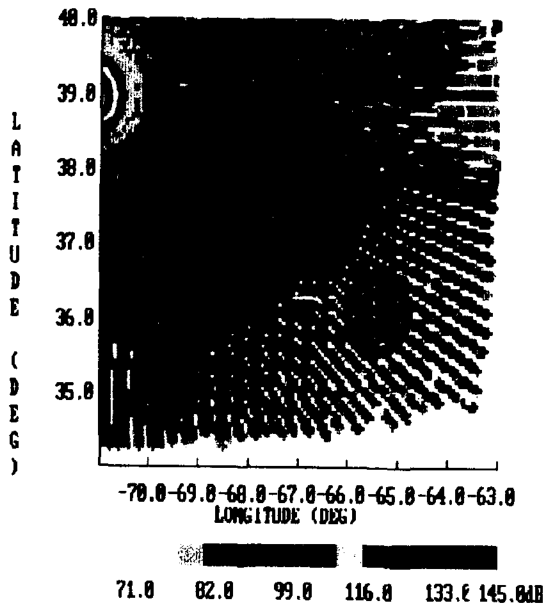

Fig. 4: Transmission loss pattern for a receiver (center of yellow patch) located in a warm-core eddy North of the Gulf Stream. Red and yellow imply regions having high submarine-detection probability.

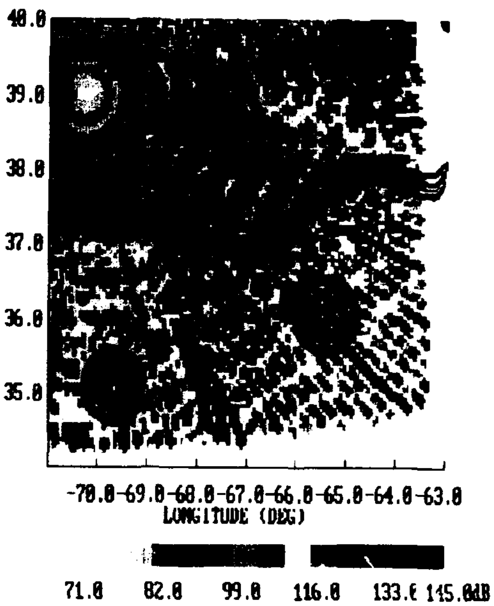

Fig. 5: Conditions same as in Figure 4, except that the receiver (center of yellow patch) is moved 35 miles east, outside the warm-core eddy. Note shadow zones produced by the Gulf Stream and the eddy to the east.

nificant is the modeling of the North Pacific at a resolution of $\frac{1}{8}°$. This is a first step toward a global $\frac{1}{8}°$ eddy-resolving model. The coupling of ocean and atmospheric models will be essential to future forecast systems. Ghil and Mechoso (1992, this issue) are presently developing techniques for the assimilation of oceanic and atmospheric data into coupled systems and for the assessment of predictability in such systems. Rosmond (1992, this issue) is approaching the ocean-atmosphere coupling through operational models. He is presently coupling the Navy global weather forecast model to the Navy ocean mixed-layer model, both of which are presently used operationally.

The Fleet Numerical Oceanographic Center is the major Navy operational facility for global, basin and regional predictions. Clancy (1992, this issue) provides an overview of the major oceanographic products at the Center. The developmental process leading to a high-resolution ($\frac{1}{8}°$ or 10–14 km) global prediction model has involved years of painstaking work in small regions. Thompson *et al.* (1992, this issue) discuss results of their work in the North Atlantic Ocean. Models, such as these that encompass large geographic areas, will, in the hierarchy concept, provide boundary conditions and model-initialization data fields to the smaller-scale local and shipboard models. Robinson (1992, this issue) gives a vivid account of what can be done aboard ship. The article relates well to current events, because the Navy is presently installing very capable computers aboard its ships specifically for this purpose.

Forecasting oceanic events will not be possible without a capability to assimilate observations, from satellites or through direct ocean measurements. Fox *et al.* (1992, this issue) have made notable progress toward assimilating data into a model of the Northwest Atlantic. The methods are being advanced for use in basin- and global-scale models developed by Hurlburt (1992, this issue) and Thompson (1992, this issue). Assessment of data assimilation methods is underway through the efforts of the Institute for Naval Oceanography. The Northwest Atlantic has been selected as the test region for a number of forecast systems, i.e., integrated ocean-prediction and data-assimilation models. The model assessment effort will be greatly facilitated by the Experimental Center for Mesoscale Ocean Prediction (ECMOP). Leese *et al.* (1992a,b, this issue) describe the assessment and ECMOP.

The Navy has a long history in ice observation and the prediction of its movement. In her article, Preller (1992, this issue), gives an excellent overview of recent achievements toward sea-ice prediction. Lastly, Horton *et al.* (1992, this issue) present results attained through a quick-reaction effort. They configured and implemented a Persian Gulf predictive model in support of Operation "Desert Storm." Reports indicate that the mine drift predictions provided by the model were very useful.

Future Efforts

The future direction of ocean prediction certainly depends on computational capabilities and our ability to efficiently access and use new high-speed computers. The implementation of ocean-atmosphere coupled nowcast (an estimate of the three-dimensional fields of temperature and salinity using climatology, observations, and analysis models) and forecast systems having 10-km horizontal resolution, up to 40 levels (surface to bottom), complete thermodynamics, and data assimilation will require processors with speeds approaching the Tera-Flop range (1 trillion floating point operations per second). In contrast, operational Cray vector computers are in the Giga-Flop range (1 to 16 billion floating point operations per second). Parallel processing supercomputers are evolving and offer the promise of achieving Tera-Flop speeds in the near future. Considerable effort is being directed toward this goal through government sponsorship and commercial enterprise. The Defense Advanced Research Projects Agency (DARPA) is, for example, heavily involved in hardware and software development of parallel processors and has established programs to accelerate the implementation of computer applications. The Office of the Chief of Naval Research is funding programs to advance the science and technology related to parallel processing. The Naval Research Laboratory, Washington, DC, has with DARPA support established a strong effort aimed at the development of applications. Other agencies, namely, the National Science Foundation (NSF), the National Aeronautics and Space Administration (NASA), the Department of Energy (DOE), and the National Oceanic and Atmospheric Administration (NOAA) are sponsoring and promoting activities aimed at the advancement of parallel processing capabilities over a wide range of applications. The next decade should provide testimony to a revelation of new computational methods and techniques, which in turn will likely lead to a revolution in environmental predictions.

The future direction of ocean prediction certainly depends on . . . new high-speed computers.

Acknowledgements

The establishment of this program is the result of considerable effort on the part of its sponsors, namely, F. Saalfeld, Director of the Office of Naval Research; P. Selwyn, Director of the Office of Naval Technology; and R. Winokur, Technical Director to the Oceanographer of the Navy. Their continuing support will unquestionably lead to the first global ocean forecasting system implemented in an operational environment. In this context, the foresight of the Oceanographer of the Navy has led to the acquisition of powerful com-

puters necessary for this job and has put in place a mechanism for their upgrade over the next 10 years. The Commander, Naval Oceanography Command, and his Technical Director, D. Durham, are assuring that the Navy will implement the best available computer systems and technology to run the models. The Navy shipboard computers, the Tactical Environmental Support System [TESS (3)] now being procured, are the product of the dedicated work of J. Jensen, now Commanding Officer of FNOC, and C. Hoffman, Director of the Environmental Systems Program Office at the Space and Warfare Systems Command. We owe thanks to Captain J. Tupez for his major contribution in organizing resources at the Naval Research Laboratory and tailoring and focusing energies toward the development and testing of prototype systems. Not to be forgotten is M. Salinas, who was instrumental in structuring the modeling program for the Navy. The Institute for Naval Oceanography continues to provide needed support leading to the development of an operational ocean forecast capability.

The authors of the articles deserve much credit for their preparation of the manuscripts. W. Lescure, the editor of the ONR Research Reviews, helped screen the manuscripts prior to submission. J. Albrittain and H. Whitlock are thanked for their assistance in typing and preparing the manuscripts for submission.

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MODELING OF THE GLOBAL AND PACIFIC OCEANS: ON THE PATH TO EDDY-RESOLVING OCEAN PREDICTION

By Harley E. Hurlburt, Alan J. Wallcraft, Ziv Sirkes, and E. Joseph Metzger

NUMERICAL weather prediction has been operational since 1955 (Thompson, 1961; Fawcett, 1962). However, insufficient data and computing power have precluded a similar capability for the ocean despite the potential for numerous military and civilian applications, e.g., antisubmarine warfare, tactical planning, optimum-track ship routing, search and rescue, long-range weather and climate prediction, sea-ice prediction, fisheries planning, design and protection of underwater structures such as oil rigs, and prediction of pollutant dispersion. Obstacles to prediction of ocean circulation arise because, historically, the ocean has been much more difficult to observe. In addition, the spatial scale for meandering ocean currents and eddies (the oceanic "weather") is an order of magnitude smaller than that for major weather systems and the meandering of the jet stream. It is only now that global-scale, eddy-resolving ocean prediction is at the threshold of feasibility. Four key technical or technological advances have made this possible.

1. Class VII supercomputers, like the Cray Y-MP8/8128, are the first capable of executing truly eddy-resolving global and basin-scale ocean models using the most efficient ocean model design available.

2. Global and basin-scale ocean models and data-assimilation techniques are being developed that can effectively utilize the expected data types. These models are designed for efficient execution on present and future supercomputers, including massively parallel machines. In the system under development by the U.S. Navy, mixed-layer models with about 20 levels in the upper 400 m are coupled to eddy-resolving ocean circulation models with about 6 layers in the vertical. This is a key strategy in developing the system, because it reduces the computational requirements by two orders of magnitude.

3. Satellites provide useful data with global coverage and adequate space-time resolution and accuracy. This includes oceanic data that the models can assimilate and also includes atmospheric forcing functions. Sea-surface height (SSH) from satellite altimetry is the single most promising source of oceanic data for operational ocean prediction, because it is strongly related to subsurface thermal structure and a major component of oceanic surface currents. Other notable satellite data sources include infrared radiometers (IR), scatterometers, multichannel microwave radiometers, and ocean-color imagers. These provide information such as the location of oceanic fronts and eddies, sea-surface temperature, and surface winds and heat fluxes.

4. Another advance is improved data communications via satellite, especially shore to ship.

These topics are discussed in more detail by Hurlburt (1984, 1987) and Malanotte-Rizzoli and Hurlburt (1987). Navy interest includes depicting the present state of the ocean, a process sometimes called "nowcasting," and forecasting its future state. Skill in doing this is measured by improvement over oceanic climatology or (more common in forecasting) the improvement over a forecast of persistence (a forecast of no change). In forecasting, duration of skill is important as well as the amount of skill.

The U.S. Navy needs to provide accurate oceanic information to ships at sea. However, as explained in the papers just cited, shore-based eddy-resolving global and basin-scale systems for nowcasting and forecasting of the ocean circulation would have greater skill and potential for broader application than *stand-alone*, limited-area models on board ships. Hence, adequate data communication and effective data compression techniques are essential. The time scale for pre-

It is only now that global-scale, eddy-resolving ocean prediction is at the threshold of feasibility.

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dictive skill should be much greater for oceanic than for atmospheric circulation, a month or more in the ocean versus a week in the atmosphere (e.g., see Hurlburt, 1984). Two-week skill has already been demonstrated for a relatively difficult region, the Gulf Stream, using only data for the *location* of oceanic fronts and eddies (Fox *et al.*, 1992, this issue). This means that, compared with weather forecasting, data is useful as input to an ocean prediction system for a longer time after the observation was taken and that the recipient of the forecast (e.g., a ship) does not need to receive the forecast as soon after the observation time to have the forecast retain useful environmental information. It also means that a ship could extract useful information from "old" forecasts for a substantial length of time without shore communication.

. . . certain oceanic anomalies can be nowcast and forecast in response to atmospheric forcing . . .

The U.S. Navy has had an operational mixed-layer prediction capability since 1981 (Clancy and Martin, 1981; Clancy and Pollak, 1983; Clancy, 1992, this issue). Before having the resources needed for eddy-resolving global and basin-scale predictions of ocean circulation, the in-house Navy effort focused on eddy-resolving models of small domains, Indian Ocean models, non-eddy-resolving global models, and on issues and techniques related to assimilation of satellite altimeter and IR data. The small domains have included semienclosed seas like the Gulf of Mexico (Hurlburt and Thompson, 1980, 1982), the Caribbean Sea (Heburn *et al.*, 1982), and the Mediterranean Sea (Heburn, 1987). High-resolution modeling of small domains also has included subdomains of major ocean basins like the Gulf Stream region (Hurlburt and Thompson, 1984; Thompson and Schmitz, 1989; Thompson *et al.*, 1992, this issue). In the Indian Ocean, 0.4° resolution was sufficient to depict major current systems and eddies (Lin and Hurlburt, 1981; Kindle and Thompson, 1989). Studies using non-eddy-resolving global models have included the Florida Straits transport (Rhodes and Heburn, 1987), the Pacific to Indian Ocean exchange (Kindle *et al.*, 1987, 1989; Murray *et al.*, 1989, 1990), the circulation in the western equatorial Pacific (Hurlburt *et al.*, 1989), and a model-data co. arison of global SSH anomalies presented in the next section. External to the Naval Ocean Modeling Program, the global simulation with $\frac{1}{2}$° resolution by Semtner and Chervin (1988) is particularly notable for both the Global and Pacific Oceans. Modern supercomputers have multiple central processing units (CPUs). The Semtner-Chervin simulation was the first large ocean simulation to demonstrate execution on all CPUs simultaneously, an important capability termed parallel processing. This capability will be essential on future massively parallel supercomputers.

The data assimilation studies for satellite altimeter and IR data have investigated topics like space-time resolution and accuracy requirements, techniques for assimilation, and inference of subsurface (even subthermocline) information from sea-surface height and sea-surface temperature (Hurlburt, 1986; Kindle, 1986; Thompson, 1986; Carnes *et al.*, 1990; Hurlburt *et al.*, 1990). Some of these modeling and data assimilation studies helped lay the foundation for the first Gulf Stream prediction system that has demonstrated forecast skill superior to persistence at both 7 and 14 days (Fox *et al.*, 1992, this issue). Interest in oceanic data assimilation has increased greatly in the last few years as evidenced by articles in this issue. Ghil and Malanotte-Rizzoli (1991) review the substantial body of literature that has already accumulated.

A Comparison of Global Sea-Surface Height Anomalies—Model versus Satellite Altimetry

As discussed by Hurlburt (1984, 1987) and Thompson *et al.* (1992, this issue, see Table 1), some features of the ocean circulation are a relatively direct integrated response to atmospheric forcing whereas others are not. This has an impact on data requirements. The Gulf Stream prediction system requires oceanic data input for nowcasting and forecasting because the meanders and eddies are primarily due to flow instabilities and are not a direct response to atmospheric forcing.

The non-eddy-resolving global modeling effort uses the premise that certain oceanic anomalies can be nowcast and forecast in response to atmospheric forcing, an approach discussed by Haney (1980), Busalacchi *et al.* (1983), Hurlburt (1984, 1987), and Cane *et al.* (1986). Some oceanic phenomena, such as the oceanic mixed layer, surface waves, and storm surges, are sensitive to daily fluctuations in atmospheric forcing. However, the class of anomalies considered here is a direct integrated response to atmospheric forcing on time scales much greater than the 1-week time scale for atmospheric predictive skill, and these anomalies are quite insensitive to errors in representing the daily fluctuations of the weather. The U.S. Navy's geodetic Earth orbiting satellite (GEOSAT) carried a satellite altimeter capable of detecting the signature of these anomalies in the SSH. This permits a global search for this class of anomalies by comparison with an atmospherically forced global ocean model.

In November 1986, after completing the geodesy mission, GEOSAT was placed into an orbit that repeated every 17.05 days, an orbit termed the GEOSAT-ERM (Exact Repeat Mission) (Born *et al.*, 1987). Figure 1 shows a global comparison of SSH anomalies during 20 September–7 October 1988 from repeat cycle 41 of the GEOSAT-ERM and from a non-eddy-resolving global ocean model. The GEOSAT data set was obtained from the National Oceanographic Data Center and was

corrected for orbit error using the Goddard Earth Model (GEM-T2) gravity model (Haines *et al.*, 1990) and software from Koblinsky *et al.* (1990). The orbit error was further reduced using a technique by Sirkes and Wunsch (1990).

The ocean model has two layers. The upper layer has temporally and spatially varying currents, density, and layer depth. The lower layer is infinitely deep and at rest. The interface separates layers of contrasting density and in the 2-layer configuration it represents the permanent pycnocline. The mean interface depth is 250 m, but large deviations occur. This type of model is often called a 1.5-layer reduced gravity model, because it has two layers but only one active layer and thus it represents only the first internal vertical mode. Furthermore, because the model is infinitely deep, only gravitational acceleration reduced by buoyancy is present. With $0.5° \times 0.7°$ resolution (lat, long) and Laplacian "horizontal" friction using an eddy viscosity of $A = 2{,}000$ m^2s^{-1}, the model is unable to resolve most eddies, although it does simulate a few eddies like the Mindanao and Halmahera eddies in the western equatorial Pacific. It was spun up from a state of rest (no motion, a flat interface, and constant density within a layer) to statistical equilibrium using the Hellerman and Rosenstein (1983) monthly wind-stress climatology, and was then continued from 1981–1989 using monthly-averaged 1,000-mb winds from the European Centre for Medium-Range Weather Forecasts (ECMWF). The 1981–1989 mean was replaced by the annual mean from Hellerman-Rosenstein, a procedure that reduces some of the biases found when the mean from ECMWF is used. Although the model is thermodynamic and accepts thermal forcing, relaxation to the annual mean density in the upper layer, obtained from Levitus (1982), was the only thermal forcing used and the only oceanic data assimilated. Thus, anomalies due to seasonal heating and cooling are included in the SSH field from GEOSAT but are not present in the model.

In the model, SSH was sampled along GEOSAT tracks at 3-second intervals to simulate the GEOSAT-ERM. Figure 1a shows the mean SSH from the model over the first 43 repeat cycles (8 November 1986–10 November 1988) of the GEOSAT-ERM and was obtained using the model GEOSAT track output. Excluding the error corrections, the simulated tracks were treated similarly to the GEOSAT data in performing an optimal interpolation to the same 1° grid used for the GEOSAT anomalies. Figure 1b shows the model deviation from the mean in Figure 1a for 20 September–7 October 1988 (repeat cycle 41), and Figure 1c shows the SSH deviation calculated from the actual GEOSAT-ERM for the same repeat cycle. The deviation is from the GEOSAT mean over the same period as Figure 1a. By themselves each of these anomaly pictures might

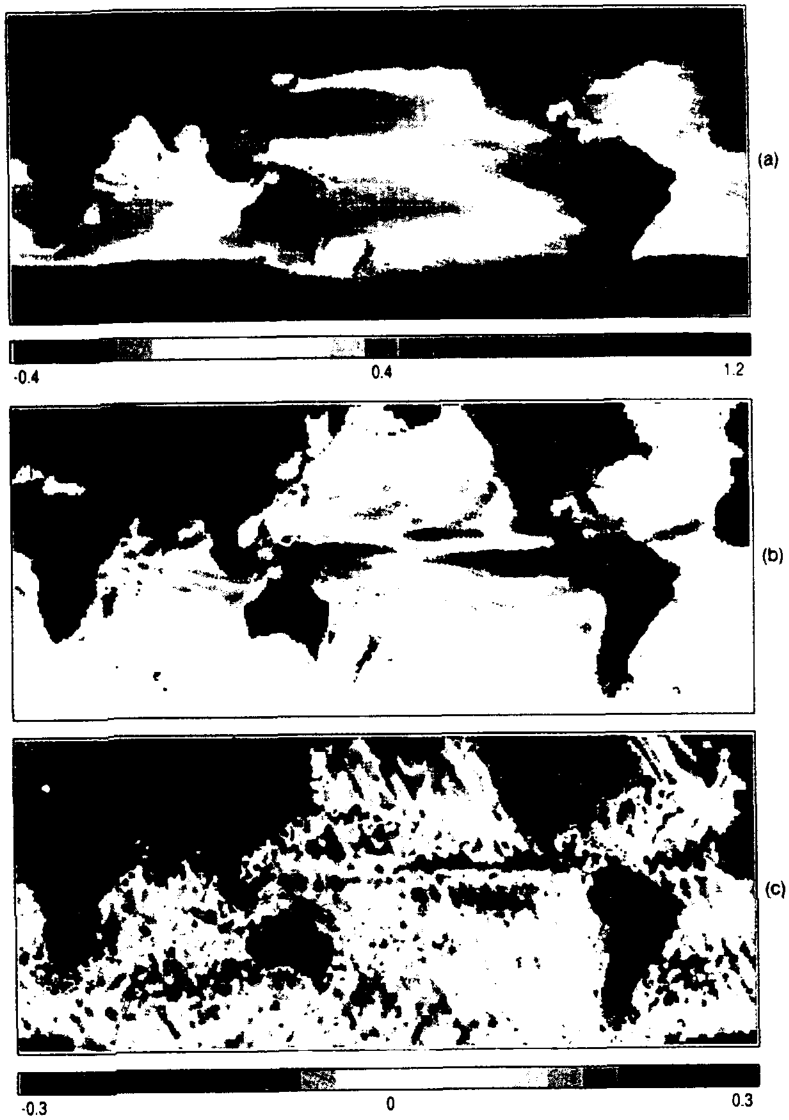

*Fig. 1: (**a**) Mean sea-surface height (SSH) for 8 November 1986–10 November 1988 from a ½°, 1.5-layer global ocean model. The SSH has been interpolated to a 1° grid from sampling along tracks of the Geodetic Earth Orbiting Satellite-Exact Repeat Mission (GEOSAT-ERM). (**b**) Model deviation from the preceding mean for 20 September–7 October 1988 (repeat cycle 41 of the GEOSAT-ERM). (**c**) GEOSAT-ERM SSH deviation from its mean over the same period. Color bars are in meters.*

lack some credibility. The model is only 1.5-layer reduced-gravity and is not eddy resolving. With a few small exceptions, only wind-driven anomalies are present. Thermally driven anomalies and most anomalies due to mesoscale flow instabilities are excluded. In addition, one might doubt the accuracy of the wind forcing over the data-sparse oceanic regions. The GEOSAT anomalies are open to question because of concerns about the accuracy of the data and the accuracy of the error corrections (such as those used for water vapor and orbit error). Because of the model-GEOSAT

agreement, each enhances the credibility of the other and of the atmospheric forcing.

For example, the GEOSAT anomaly field shows a distinctive, narrow band of positive anomaly extending across most of the Pacific Ocean between 5° and 10°N. This might be dismissed as being due to water-vapor error associated with the intertropical convergence zone (ITCZ). However, the model shows the same feature as well as the negative anomalies on either side in the central and eastern Pacific. Negative sea-level anomalies are consistent with a shallowing of the thermocline and negative sea-surface temperature anomalies. In addition, the sea level in the western equatorial Pacific is relatively high and the SSH tilt along the equator is relatively large in both the model and GEOSAT. This result occurs because 1987 was an El Niño year and 1988 was an anti-El Niño year. Consistent with this pattern of anomalies, the model shows a strong westward South Equatorial Current (SEC) along the equator and a northward shift in the eastward North Equatorial Countercurrent (NECC) (represented by the band of positive anomaly between 5° and 10°N).

. . . satellite altimetry can be assimilated to represent features not driven by atmospheric forcing . . .

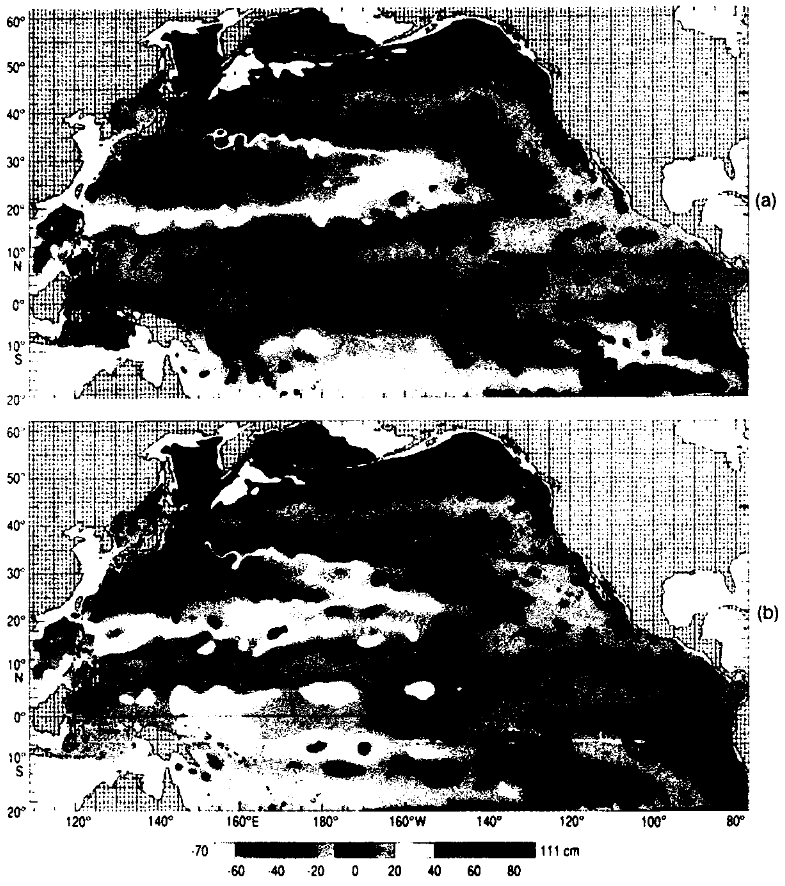

Fig. 2: Sea-surface height simulated by a $\frac{1}{8}$°, 6-layer Pacific ocean model for (a) 17 December 1986 and (b) 16 December 1989. The model has realistic bottom topography as shown in Figure 3. Color bar is in centimeters and the extreme values labeled on the color bar are the extremes over the two dates. Meandering contours and eddies are ubiquitous, and strong interannual differences are evident. The simulation was performed on the Cray Y-MP8/8128 at the Naval Oceanographic Office, Stennis Space Center, MS, as part of the Naval Ocean Modeling Program.

Other regions where the model and GEOSAT data reveal similar anomalies are easily found, as well as regions of disagreement. The best agreement is at low latitudes where there is a relatively rapid response to changes in the wind field. However, corresponding anomalies between the model and GEOSAT are found at mid latitudes despite the model's lack of mesoscale variability and seasonal anomalies due to heating and cooling, which are relatively important at these latitudes. One example is the distribution of positive anomalies found in the Kuroshio Extension region east of Japan. Compared with the 2-year mean, the Kuroshio Current was strong south of the Japanese island of Honshu, and the Kuroshio Extension was shifted slightly to the north in the model. The 0.5° × 0.7° 1.5-layer model does not simulate the meanders and eddies, which are prevalent in the region. In an ocean prediction model with sufficiently high horizontal resolution, the SSH anomalies from satellite altimetry can be assimilated to represent the features not driven by the atmospheric forcing and to improve the accuracy of those that are. Assimilation of GEOSAT altimetry has been demonstrated for the California Current region by White *et al.* (1990).

Poleward of the subpolar fronts in both hemispheres, positive wind-stress curl drives an upward displacement of the interface between the two layers in the model. Vertical mixing between the layers is used to prevent the interface from outcropping at the surface. When vertical mixing occurs across a model interface, that interface is described as ventilating. In the 1.5-layer reduced-gravity model, this ventilating results in the loss of wind energy to the infinitely deep abyssal layer of the model and the presence of a shallow, flat interface between the layers. As a result the model has no significant geostrophically balanced currents or anomalies within the subpolar gyres (i.e., poleward of about 45° latitude).

A $\frac{1}{8}$° Eddy-Resolving Model of the Pacific Ocean North of 20°S

In November 1990 a Cray Y-MP8/8128 was installed at the Naval Oceanographic Office, Stennis Space Center. This computational power made it feasible to develop $\frac{1}{8}$°, eddy-resolving global and basin-scale ocean models using an efficient ocean model design, layered models with about 6 layers in the vertical. The plan is to couple these models to the Navy's operational mixed-layer forecast model, TOPS (Thermal Ocean Prediction System), and via TOPS to NOGAPS, the Navy Operational Global Atmospheric Prediction System (Clancy, 1992, this issue; Rosmond, 1992,

this issue). In August 1990 in preparation for the Navy's Cray Y-MP, the Cray Y-MP8/6128 operated by the Army Corps of Engineers at Vicksburg, MS, was used to perform the first $\frac{1}{8}^\circ$ simulation for any major ocean basin (which had realistic topography), a $\frac{1}{8}^\circ$ model of the Pacific Ocean north of 20°S. In November 1990 this model became the first user application on the Navy's Cray Y-MP8/8128.

In the layered formulation used for the Pacific model, the model equations are vertically integrated through each layer. The model is a descendant of the semi-implicit free-surface model of Hurlburt and Thompson (1980) but with extended capability (Wallcraft, 1991). It is similar to the 1.5-layer reduced-gravity model described earlier except that it is finite-depth with realistic bottom topography, thermodynamics are excluded (density is constant within a layer), greater horizontal and vertical resolution are used, and the numerical treatment of the gravity waves is implicit. Figure 2 shows two SSH snapshots from a 6-layer version of the Pacific model. The bottom topography is shown in Figure 3. The horizontal resolution is 0.125° × 0.176° (lat, long) for each variable or about 15 km at mid latitudes. The model also includes all of the deep marginal seas, such as the Bering Sea, the Sea of Okhotsk, the Sea of Japan, the South China Sea, the Sulu Sea, and the Indonesian archipelago (from north to south along the western boundary). The model boundary is the 200-m isobath with a few exceptions, such as the straits connecting the Sea of Japan. Artificial solid boundaries are placed at 20°S and in the straits at the southern boundary of the Indonesian archipelago. The mean interface depths are 125, 275, 500, 750, and 1000 m, but large deviations from these occur in regions like the subarctic and subtropical gyres where the SSH deviations also are large. The density contrasts between the layers at these interfaces are 1.75, 0.87, 0.43, 0.23, and 0.42 kg m^{-3}, respectively. The values are means over the model domain determined using the Levitus (1982) oceanic climatology. The "horizontal" eddy viscosity is A = 100 m^{2}s^{-1}, low enough to permit vigorous flow instabilities and numerous eddies.

The Cray Y-MP8/8128 has eight independent CPUs. The $\frac{1}{8}^\circ$, 6-layer Pacific model uses all eight CPUs simultaneously (parallel processing) to achieve a sustained computational rate of 1.1 billion floating point operations (adds and multiplies) per second. In this mode the model performs a 1-year simulation in slightly <6 hours as measured by a clock on the wall.

Starting from rest, the model was spun up to statistical equilibrium at $\frac{1}{4}^\circ$ resolution using the Hellerman-Rosenstein monthly wind-stress climatology, and then continued another 15 years at $\frac{1}{8}^\circ$ resolution. Finally it was run 1981–1989 using monthly averaged ECMWF 1000-mb winds

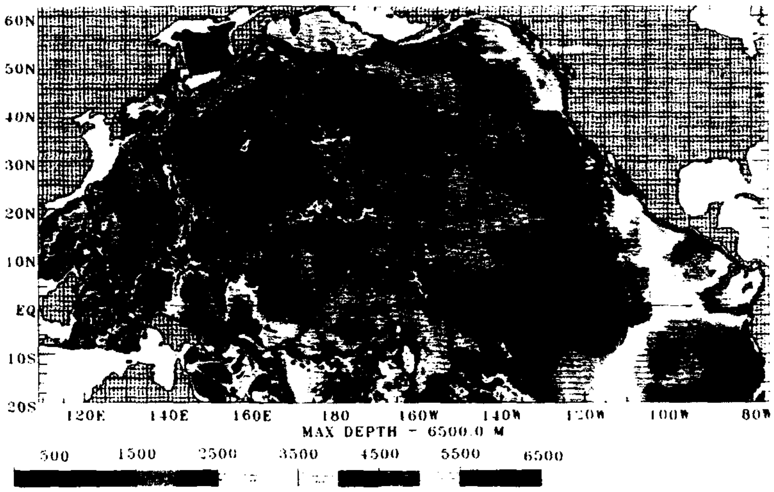

Fig. 3: $\frac{1}{8}^\circ$ Pacific model bottom topography. Using 6,500 m as a reference depth, the topographic amplitude shown here was multiplied by 0.73 to confine the topography to the lowest layer of the model. Color bar is in meters.

with the 1981–1989 mean replaced by the annual mean from Hellerman-Rosenstein. No oceanic data were assimilated in this purely wind-forced simulation.

Results from the $\frac{1}{8}^\circ$ Pacific Simulation

Figure 2 shows the model simulation of the SSH for 17 December 1986 and 16 December 1989. Striking features include the following: 1) the ubiquitous nature of meandering contours and eddies even though the SSH variability is high only in regions noted for strong meandering currents and eddies and 2) the interannual differences between December 1986 and December 1989, on larger scales as well as the smaller scale of individual meanders and eddies. Larger-scale anomalies are prominent in the non-eddy-resolving global model as well (Fig. 1), but they are more prominent at mid and high latitudes in the $\frac{1}{8}^\circ$ Pacific model. Most of the simulated meanders and eddies would, of course, not exhibit one-to-one correspondence to those observed because they are due to flow instabilities. However, the current meanders and eddies are much more numerous and stronger when the model is forced by the interannually varying winds than when it is forced by the Hellerman-Rosenstein monthly wind-stress climatology. When monthly averages over 1981–1989 are formed, the amplitude of the seasonal variations in wind stress and wind-stress curl for the ECMWF 1,000 mb winds averaged over the model domain are similar to those for Hellerman-Rosenstein. This occurs when a drag coefficient of $C_d = 1.5 \times 10^{-3}$ and an atmospheric surface density of $\rho_{air} = 1.2$ kg m^{-3} are used with the ECMWF winds.

Figure 2 shows the basic features of the upper ocean circulation in the equatorial and North Pa-

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cific. The subtropical and subarctic gyres are clearly evident. They are separated by the Subarctic Front at ~40–45°N. However, the strongest portion of the subtropical gyre is bounded on the north by the Kuroshio Extension at ~32–36°N, giving a double frontal structure separating the strongest portion of the two gyres. Except within a few degrees of the equator, the near-surface currents tend to follow the isolines of the SSH, with high SSH to the right in the northern hemisphere and to the left in the southern hemisphere. The stronger currents are marked by narrow ribbons of color. The subarctic gyre is bounded on the north by the Alaskan Stream off the south coast of Alaska and the south side of the Aleutian Island Chain from roughly 145°W to 170°E. On the west it is bounded by the East Kamchatka Current, which flows along the coast from the western Bering Sea (starting at 60°N) to the mouth of the Okhotsk Sea (at 48°N) and is bounded on the southwest by the Oyashio Current southwestward from the mouth of the Okhotsk Sea, and then eastward along the narrow ribbons of color near 42°N. South of Kodiak Island at 153.5°W, the model's mean transport for the Alaskan Stream is 14.3 Sv (i.e., 14.3×10^6 m^3s^{-1}) close to estimates from hydrography (Reed, 1984) and close to the prediction from Sverdrup flow using the annual mean Hellerman-Rosenstein wind-stress climatology.

. . . the patterns of eddies show substantial interannual variation.

In contrast to the Alaskan Stream, the eastern boundary currents in the subarctic gyre region undergo large seasonal fluctuations in the model. These currents flow along the eastern boundary of the model to the eastern end of the Alaskan Stream. They are strong and northward in fall and winter and are weak and southward in spring and summer. In 1986, the strongest northward flow occurred in January. Starting in February, the model simulated a series of prominent anticyclonic eddies along the coast at the beginning of the transition from northward to southward flow, the most prominent being those off Sitka, Alaska and the Queen Charlotte Islands. Later, the eddies were found between southward flow along the coast and northward flow remaining offshore. The eddies moved offshore, and a weaker series of cyclonic eddies formed shoreward before the return of northward flow along the coast. Three anticyclonic eddies that formed off Sitka, Queen Charlotte, and Vancouver Island during February–March 1986 are evident in the SSH for 17 December 1986 (Fig. 2a) at (respectively) 55°N, 139°W; 51°N, 135°W; and 49°N, 132°W. These are visible as a lighter shade of blue embedded in a darker shade of blue. South of them, cyclonic eddies are found in the region 40–50°N, 125–130°W (visible as a darker shade of blue embedded in a lighter shade). This sequence of events and the patterns of eddies show substantial interannual variation. In 1989, the strongest northward flow in the model occurred in March, and the subsequent anticyclonic eddies were fewer and weaker. By 16 December 1989, only one at 53°N, 136°W is visible in this region (Fig. 2b).

Unlike the global model, the 6-layer Pacific model has a robust time-dependent circulation in the subarctic gyre. The interfaces between the upper layers are ventilated by positive wind-stress curl as described for the global model, but at least two of them do not ventilate over all or almost all of the gyre and a third one over a large part of it. Interior to the subarctic gyre a significant countercurrent runs roughly adjacent to the Alaskan Stream, similar to the picture by Dodimead *et al.* (1963) and consistent with the Sverdrup flow driven by the annual mean Hellerman-Rosenstein wind stress.

The interiors of the subarctic and subtropical gyres also contain transient fronts and frontal segments. This is particularly striking in the subtropical-gyre simulation for 16 December 1989 (Fig. 2b), where three large-scale ridges in the SSH extend eastward between 17° and 32°N. These imply alternating bands of eastward and westward flow within the subtropical gyre. There is little evidence of these in the simulation for 17 December 1986 (Fig. 2a).

The subtropical gyre is bounded on the south by the North Equatorial Current (NEC) at ~10–18°N. This current splits at the Philippines coast to form the northward Kuroshio Current and the southward Mindanao Current. The mean split point occurs near 14°N. From here the Kuroshio Current flows northward along the eastern Philippines coast and then along the western boundary of the model until it separates from the coast of Japan near 35°N, 140°E to flow eastward as the Kuroshio Extension. The Mindanao Current flows southward along the Philippines coast from the split point to ~3°N. It is the western boundary current for an elongated gyre with the NEC on the north side and the NECC on the south side (along ~5°N). The gyre is marked by a trough in SSH centered at 7–9°N. This trough and the bounding currents are much stronger in the simulation for December 1989 than in that for December 1986. In addition, the gyre is narrower and centered farther north in December 1989, but the northern boundary is farther south. Comparing December 1989 and December 1986, the eastern end of the NEC near 140°W is at 13° versus 19°N, and the split point at the western end is at 12.5° versus 15°N. Farther south, the SSH tilt along the equator and the South Equatorial Countercurrent near 9°S were stronger in December 1989. These results for the tropics are consistent with the El Niño present during December 1986, but may be due in part to a trend in the tropical ECMWF 1,000-mb winds.

The 6-layer model has two shallow layers. This design and vertical mixing allows the simulation

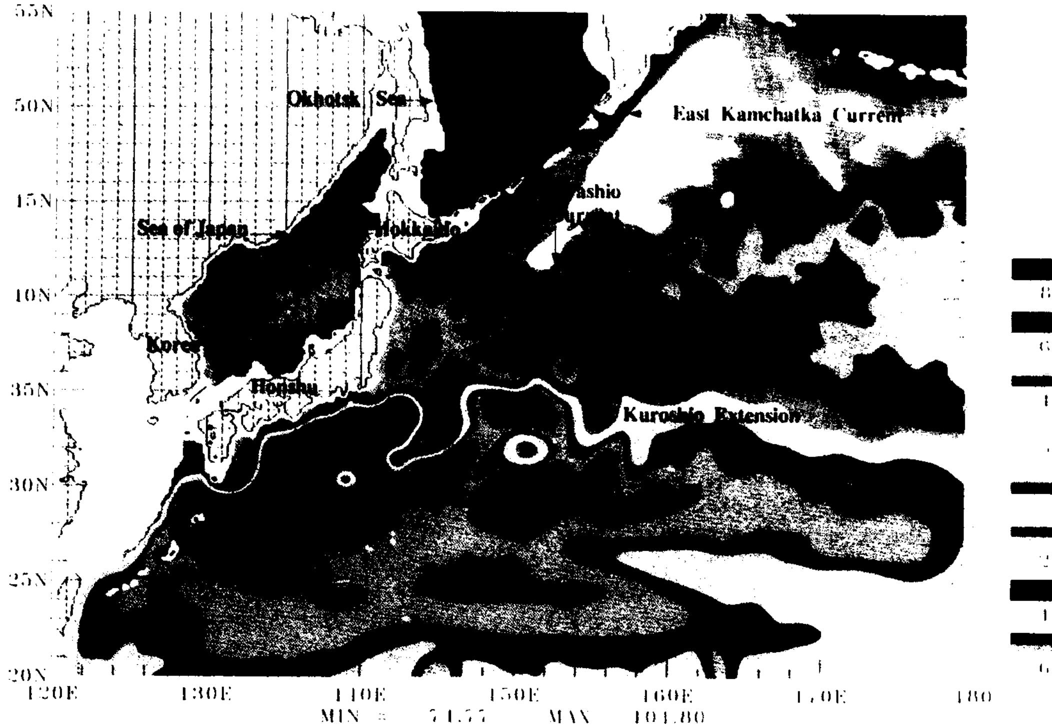

Fig. 4: Magnified view of the sea surface height in the northwest Pacific on 14 January 1983 as simulated by the $\frac{1}{8}°$ Pacific model. The simulated meanders and eddies would not in general correspond to those observed on the same date because they are primarily due to flow instabilities. Color bar is in centimeters.

to exhibit a westward SEC at the surface and an eastward Equatorial Undercurrent (EUC) in the second layer. The behavior of the undercurrent is sensitive to the mixing depth and the choice of mean layer depths in at least two ways: the strength of the undercurrent and whether it unrealistically extends into the third layer. However, realistic behavior for the undercurrent is consistent with realistic mixing and interface depths. In this simulation the depths of the first two interfaces are slightly too shallow and/or the mixing depths too deep. As a result, the undercurrent is too strong and it extends into the third layer.

The Northwest Pacific

Figure 4 shows a magnified view of the simulated SSH in the NW Pacific for 14 January 1983. This should be used in comparison with 17 December 1986 and 16 December 1989 from Figure 2 and the composite of frontal analyses from satellite IR shown in Figure 5. In all, the northward Kuroshio Current is clearly evident along the western boundary south of Honshu, and the southward East Kamchatka Current is found along the western boundary northeast of the mouth of the Okhotsk Sea. Also evident are the Kuroshio Extension along roughly 35°N and

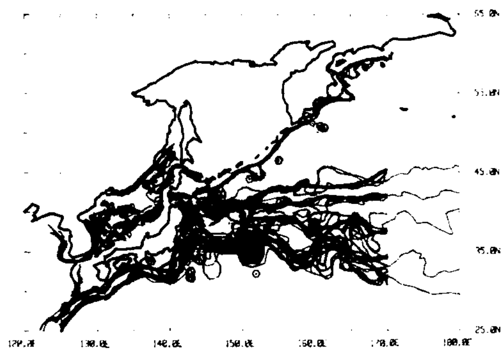

Fig. 5: Composite of oceanic frontal analyses in the northwest Pacific. These analyses are prepared routinely from satellite infrared measurements by the Operational Oceanography Center at the Naval Oceanographic Office, Stennis Space Center, MS. This composite covers 10 April–19 July 1991 at ~3-day intervals. From 170° to 180°E only one analysis is plotted. It shows the five frontal boundaries plotted east of Japan. From north to south they are the northern and southern boundaries of the Oyashio Current/Subarctic Front, the transition front, and the northern and southern boundaries of the Kuroshio Extension. (Courtesy Dale Ordish, Operational Oceanography Center.)

The simulated meanders and eddies . . . are primarily due to flow instabilities.

the O:ashio/Subarctic Frontal system along 40–45°N.

One issue in this region is how the Kuroshio Current feeds part of its transport into the Subarctic Frontal region. More viscous simulations, simulations which are more linear, and simulations excluding the Sea of Japan have shown an unrealistic northward surface current along the east coast of Honshu. The eddy-resolving, strongly non-linear simulations with realistic bottom topography and an open Sea of Japan offer three more realistic alternative routes for the Kuroshio to Subarctic Front transport. The first of these is a mean transport of 2.8 Sv through the Sea of Japan, with two distinct branches evident in Figures 2, 4, and 5. One branch in the Sea of Japan is found along the north coast of Honshu, the other follows the Korean coast and then flows eastward across the basin at about 40°N. The second is an inertial route that is seen near 148–150°E. The third route is bifurcation of the Kuroshio near the Shatsky Rise, which is centered at 32.5°N, 158.5°E (Fig. 3). In the 6-layer simulation, this route is subsurface and is not evident in the SSH shown in Figures 2 and 4. The purely wind-driven simulation also exhibits weak meridional overturning with a net transport of 3.5 Sv southward across 39.5°N in the top two layers and compensating northward flow in the other layers. In the deeper layers, northward flow is found in the route along the east coast of Honshu.

Frontal analyses like those composited in Figure 5 are produced routinely from satellite IR by the Operational Oceanography Center at the Naval Oceanographic Office. Frontal locations from IR can be valuable input to an ocean prediction system using an eddy-resolving model like the $\frac{1}{8}$° 6-layer Pacific model. This information can be used to locate eddies and to fix the phase of meanders like those seen in Figures 2 and 4. In addition, they can be used to determine the location of major fronts such as the Kuroshio north wall (e.g., see Fox *et al.*, 1992, this issue). Figure 5 clearly shows standing meanders on the Kuroshio, as does the Pacific model and the Generalized Digital Environmental Model (GDEM), the Navy's oceanic climatology (Teague *et al.*, 1990). The GDEM climatology shows a ridge near 150°E that is particularly common in the model and is present on all three of the dates shown.

> Frontal locations from IR [infrared radiometers] can be valuable input to an ocean prediction system . . .

The Western Equatorial Pacific

Figure 6 compares the mean currents from observations and the $\frac{1}{8}$° 6-layer Pacific simulation during July–September 1988 in the western equatorial Pacific. Figure 6a shows observations of currents reported by Lukas *et al.* (1991), which were obtained from drifters drogued at a 15 m depth and from acoustic Doppler current profiler (ADCP) measurements. Figure 6 also shows currents from the first (b) and second (c) layers of the

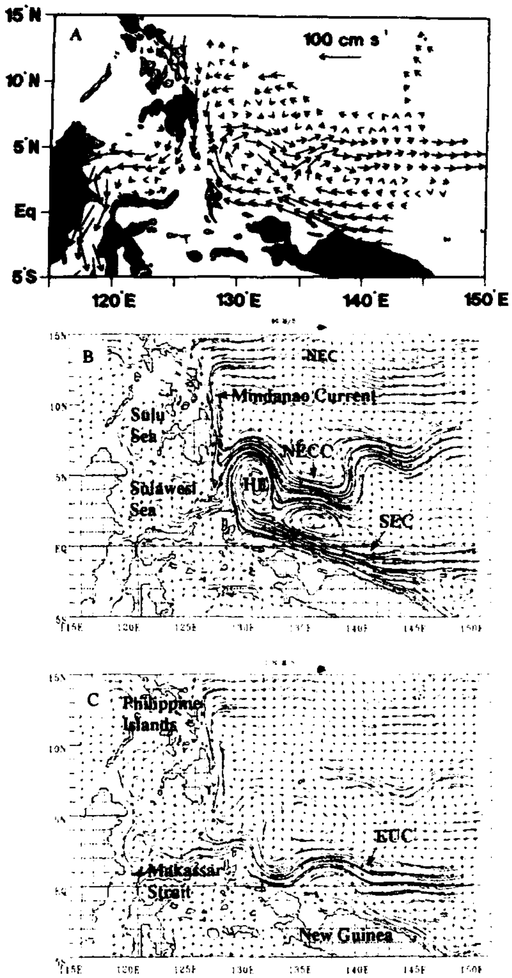

*Fig. 6: (**a**) Drifter velocity vectors and automatic Doppler current profiler (ADCP) measurements averaged on 1° squares for July–September 1988, then smoothed (from Lukas et al., 1991). (**b** and **c**) Mean velocity vectors for July–September 1988 simulated by the $\frac{1}{8}$°, 6-layer Pacific Model in (**b**) layer 1 and (**c**) layer 2. Layer 1 is the surface layer, layer 2 the layer containing the Equatorial Undercurrent. Velocity values from the model were sampled at 3-day intervals and then averaged in time.*

model. The appropriate comparison is between the observations and the upper layer of the model. The second layer is included to show the equatorial undercurrent and the dramatic change in the currents with depth in just the upper 200–300 m.

The basic features of the flow shown by the model and the observations compare remarkably well despite the gross differences in sampling, errors in the atmospheric forcing, deficiencies in the model, and the presence of flow instabilities (which can cause two simulations using the same

model and wind forcing to diverge in some respects, if there is any difference in the initial state). The lack of Pacific-Indian Ocean exchange is a serious deficiency in the model for this region. As a result, the Pacific model does not show the strong southward flow down the Makassar Strait (found by the drifters), a feature present in the global model discussed earlier. However, other major features in the data and the model correspond quite well. These include the southward Mindanao Current along the east coast of the Philippines and the westward SEC north of New Guinea, both of which feed into the eastward NECC that meanders along 5°N. In addition, there is a loop into the Sulawesi Sea, which is westward on the north side and eastward on the south side. Between the SEC and the NECC, two major anticyclonic eddies are found in both the observations and the model. The well-known and quite persistent Halmahera Eddy (HE) is centered near 4.5°N, 130.5°E in both the model and the observational analysis during July–September 1988. Also, both show a cyclonic eddy pair elongated SE-NW north of the trough in the NECC near 135°E. The NEC found in the model at ~10–18°N was only sparsely sampled by Lukas *et al.* (1991). During July–September 1988, the model shows that the mean location of the split between the northward Kuroshio Current and the southward Mindanao Current at the Philippines coast occurs at 14.5°N, close to the mean location found in the GDEM climatology (Hurlburt *et al.*, 1989). Comparison with Figure 2 shows the strong variability throughout this region.

In the second layer of the model the NECC is much weaker and the Mindanao Current and the westward flow along New Guinea both feed into the eastward EUC (Fig. 6c). The second layer also shows a westward current at 3–5°N. This current and the Mindanao Current feed into both the NECC and the EUC.

Conclusions

The articles in this issue demonstrate two major milestones on the path to eddy-resolving global ocean prediction. One is the robust demonstration of forecast skill for the Gulf Stream at both 7 and 14 days (Fox *et al.*, 1992, this issue). The other is the $\frac{1}{8}$° eddy-resolving models of major ocean basins that have realistic behavior, a milestone made possible by Class VII computers like the Cray Y-MP8/8128. These models are also valuable tools for studying ocean circulation, a capability enhanced by the modularity of layered models. The results of these and other simulations will be discussed in greater depth in future articles, including model-data comparisons.

. . . $\frac{1}{8}$° eddy-resolving models of major ocean basins that have realistic behavior, a milestone . . .

Acknowledgements

This is a contribution to the Global Ocean Prediction System project at the Naval Research Laboratory (NRL) under program elements 62435N and 63207N and to the North Atlantic Ocean Prediction System project at the Institute for Naval Oceanography under program element 61153N. All of the preceding are part of the Naval Ocean Modeling Program managed by Robert Peloquin. This is also a contribution to the Eddy-resolving Global Ocean Model project and the Kuroshio Extension Regional Experiment Accelerated Research Initiative at NRL, sponsored by the Office of Naval Research under program element 61153N. The ocean model simulations were performed on the Cray Y-MP8/8128 at the Naval Oceanographic Office, Stennis Space Center, Mississippi. We thank Ashley McManus for her work on some of the color graphics and Charles Horton at the Naval Oceanographic Office for his assistance.

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DATA ASSIMILATION AND PREDICTABILITY STUDIES FOR THE COUPLED OCEAN-ATMOSPHERE SYSTEM

By Michael Ghil and Carlos R. Mechoso

As OCEANIC DATA SETS increase dramatically in quality and quantity in the near future, and both oceanic and atmospheric models improve apace, the predictability of the coupled ocean-atmosphere system will become more important on the theoretical level and more critical on the practical level. Predictability of the atmosphere with prescribed sea-surface temperatures (SST) has been evaluated; numerous studies indicate that two initially very similar atmospheric states will lead to time evolutions that on the average diverge and become uncorrelated over an interval on the order of 2 weeks. There is also a growing literature on the predictability of the upper ocean with prescribed atmospheric wind stress and heat fluxes. But the variability, and hence predictability, of the coupled system is quite different from the sum, product, or any other simple function of its parts (Ghil *et al.*, 1991a).

The long-term goal of our work at UCLA is to provide a description, understanding, and prediction of the coupled ocean-atmosphere system as complete and reliable as that which now exists for the atmosphere alone. Our approach is to develop methods for data assimilation from sequential estimation and control theory and for predictability studies from dynamical systems and statistical turbulence theory; these methods are then tested on a variety of models, ranging from simple models amenable to analytical treatment to coupled ocean-atmosphere general circulation models (GCMs).

Data Assimilation For The Coupled Ocean-Atmosphere System

The ambitious and elusive goal of data assimilation is to provide a dynamically consistent "motion picture" of the atmosphere and oceans in three space dimensions with known error bars. The ingredients for generating this four-dimensional space-time movie are a large number of observations with different spatiotemporal distributions and error characteristics, on the one hand, and an imperfect knowledge of and ability to solve the equations of fluid motion, on the other.

The purposes of generating such a movie can differ: in numerical weather prediction and in the emerging discipline of ocean forecasting, the main emphasis is on short "loops" between successive initial states for subsequent prediction, separated by 1 day (in the atmosphere) or 1 week to 1 month (in the oceans). In climate-related problems, whether atmospheric or oceanic, the emphasis is on full-length "feature movies," based on all the information available for long-time intervals, e.g., for the entire duration of a field experiment or of even longer historic data records.

In meteorology, data assimilation is a well-established subfield described in books such as Bengtsson *et al.* (1981) and Daley (1991). In oceanography, the increase in data sets as well as the improvement in models are working a true revolution in the need for and interest in data-assimilation methods. The general problem of data assimilation for the atmosphere and oceans is discussed by Ghil (1989, 1990) and by Ghil and Malanotte-Rizzoli (1991).

A considerable number of methods with increasing degrees of sophistication have been developed for and applied to the assimilation of atmospheric and oceanic data. The key difficulty resides in ascertaining the relative confidence one has in, and therefore the relative weights one should assign to, various observations and various model predictions. In direct insertion, local observations are given complete credence and are used to simply replace model predictions at the time of observation. In variational methods with strong constraints, the model is considered perfect and observations are only allowed to help pick the succession of model predictions that are closest

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to the observations. Other methods try to use different theoretical ideas and computational resources, the common purpose being to assign relative weights to model values and observed values in inverse proportion to their estimated square errors; these methods include successive corrections, nudging, so-called optimal interpolation (OI) and variational methods with weak constraints (Daley, 1991; Ghil and Malanotte-Rizzoli, 1991).

The simplest way to test the performance of a data-assimilation method . . . is to run a so-called identical-twin experiment.

The best estimate of the current state of a geophysical flow field, based on past and current observations, is provided in the case of linear flow equations by the Kalman (1960) filter. The filter makes optimal use of information about the observational errors and the model errors to calculate the above-mentioned relative weights in computing the current flow-field estimate. It can be generalized to the more realistic nonlinear equations used nowadays in dynamic meteorology and physical oceanography via the so-called extended Kalman filter (EKF: Ghil *et al.*, 1981; Miller and Ghil, 1990). At UCLA, we have applied a full suite of the data-assimilation methods sketched above to models of varying complexity and with varying resolutions of the mid-latitude and tropical ocean.

Todling and Ghil (1991) investigated the ability of a data-assimilation system based on the Kalman filter to track rapidly developing barotropic and baroclinic instabilities in the atmosphere and oceans. The simplest way to test the performance of a data-assimilation method, used in conjunction with a given model and a given set of observations, is to run a so-called identical-twin experiment. First, a control integration is carried out with a given initial state; this integration is considered to provide the correct succession of states of the flow fields and therefore is also often named "the nature run." Next, random perturbations are added to the initial state (to reflect our lack of complete and accurate knowledge thereof) and to the model equations; this run is considered to represent the succession of states that we would obtain in the absence of any observations. Finally, an assimilation run is made with the same initial state as in the second, perturbed run, but using observations extracted from the control run at selected locations (according to an existing or planned observing pattern) and is blended with the model-predicted values while applying the weights provided by the assimilation method under study. The difference between the model state at any given time in the assimilation run and that in the control run is referred to as model anomaly and is measured typically by the corresponding root-mean-square (RMS) error; the performance of the data-assimilation method is reflected by the reduction of this error over time with respect to its initial value, or with respect to another appropriate comparison value (e.g., that in the second run, without observations).

For the barotropic case, Todling and Ghil (1991) produced an identical-twin simulation by adding random perturbations to the results of a run performed using a shallow-water model, initialized with an unstable velocity profile (Fig. 1). In the assimilation runs, the observations were assimilated using the Kalman filter method. In this way, Todling and Ghil (1991) showed that the Kalman filter results in a substantial reduction of the initial error, even for a limited number of observations (Fig. 2). Furthermore, they showed that observations made within the region of most unstable flow are more effective for the assimilation. This work is being extended to the baroclinic case; preliminary results for this case were reported by Todling and Ghil (1990).

An important problem for ocean prediction is the compensation of errors in atmospheric wind-stress data by the use of ocean data. This problem was explored by Hao (1991), using a linear, reduced-gravity model of a tropical ocean basin and an assimilation method based on OI. Hao forced the model with biased wind stresses and compared the effect of assimilating (at selected locations) either the height of the free surface (as would be the case if altimeter data were used) or the zonal velocity (as would be the case if current-meter data were used). Hao found that error reduction due to assimilation varies between the western, central, and eastern parts of the basin, and between the height and velocity field (Fig. 3). The dependence

Fig. 1: The one-layer version of the shallow-water model exhibits strong barotropic instability for a basic meridional velocity profile of cosine-square shape (Kuo, 1973). Fields are shown after 10 days of model evolution. Units are m for heights; reference arrow (at top): 54 ms^{-1} for winds. (After Todling and Ghil, 1991.)

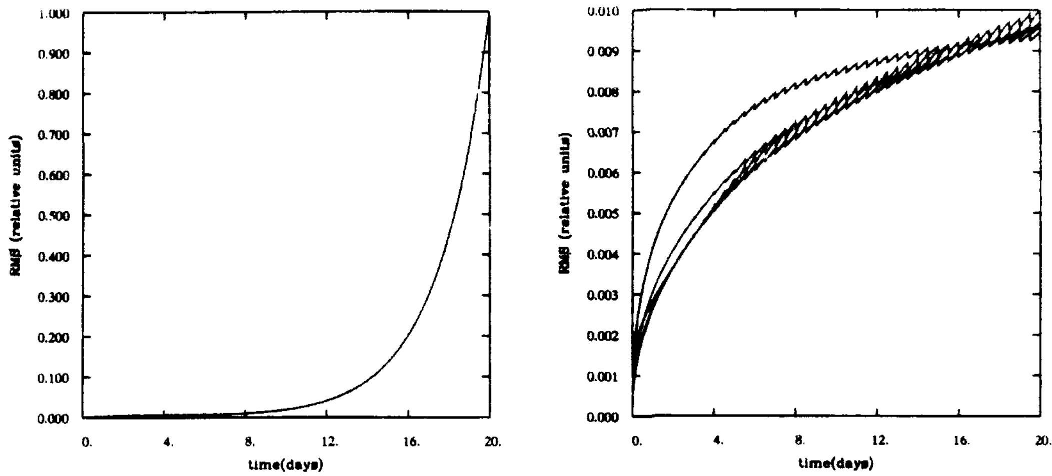
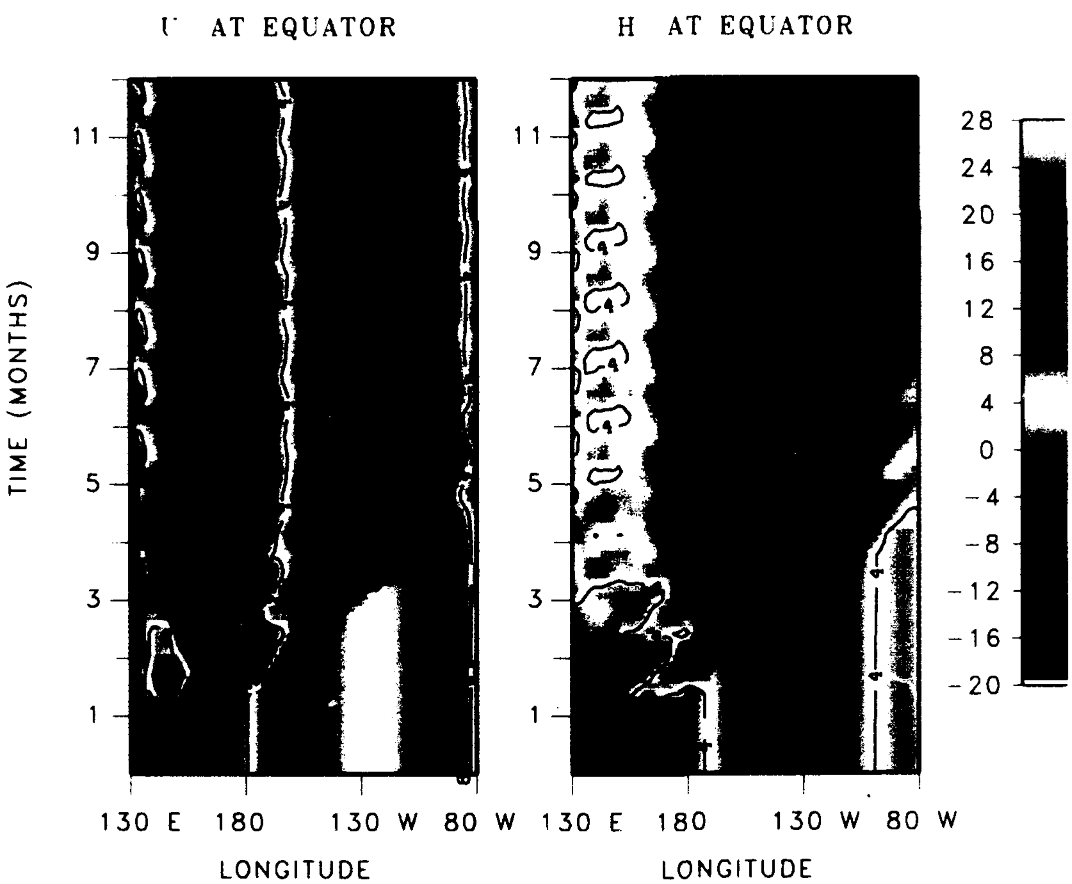


Fig. 2: Expected root-mean-square (RMS) deviation for zonal velocity (blue), meridional velocity (green), heights (purple), and total energy (red) from a Kalman filter applied to an unstable shallow-water model. The panel on the left shows the case without update by observations; curves are normalized by their maximum values and coincide due to the common growth rate of the unstable mode. Panel on the right shows curves for the case with update by observations every 12 hours; curves are normalized by corresponding values in the left panel.



. . . the Kalman filter results in a substantial reduction of the initial error, even for a limited number of observations . . .

Fig. 3: Data assimilation with an optimal interpolation (OI) scheme in the tropical Pacific. Model anomalies are shown when observations of height and zonal velocity are made only along a meridional line in the western part of the basin, at 140°E. Zonal-velocity anomaly (left), and thermocline-depth anomaly (right). Values are in nondimensional units, with a contour interval of four units. (After Hao, 1991.)

of error reduction on location and on the oceanographic field that is being updated arises from the special properties of equatorial waves, which propagate information from data-sparse to data-rich regions of the ocean and transfer information from one field variable (height or velocity) to another.

What can be expected from a data-assimilation method in the presence of strong nonlinearities? Miller and Ghil (1990) address this issue by applying three versions of the extended Kalman filter and several variational methods to a number of geophysical models of increasing complexity. Their provisional answer is that the most advanced assimilation methods are expected to capture transitions between different flow regimes and to provide reliable error estimates in cases of chaotic behavior.

Predictability Studies For The Ocean And Atmosphere

Our predictability studies have focused on two complementary aspects of the problem: instabilities in the open ocean and coastal regions, which limit predictability; and the stability of localized coherent vortex structures, which enhance predictability. We have found shortwave instabilities with rapid growth rates in both a coupled density front with zero potential vorticity (Paldor and Ghil, 1990) and a two-layer coastal front with the interface emerging at some distance from the coast (Paldor and Ghil, 1991). We are proceeding to the nonlinear, viscous treatment of the isolated front, which corresponds to the oceanographically most interesting case of the Gulf Stream north wall.

The coupled GCM [General Circulation Model] produces a realistic simulation of the seasonal cycle . . . , without any flux correction.

Concerning the stability of coherent vortices, we have demonstrated that, in agreement with field observations and numerical experiments, stationary (Sakuma and Ghil, 1990) as well as eastward- and westward-traveling (Sakuma and Ghil, 1991) vortex pairs are linearly stable. Our results provide a stronger criterion for the stability of such pairs than was previously available. The physical basis of these results can be explained by the stabilizing effect of rotation on geophysical flows in Sakuma and Ghil (1992).

Modeling Of The Coupled System

The oceanic global circulation model (OGCM) of the Geophysical Fluid Dynamics Laboratory at Princeton University and the atmospheric global circulation model (AGCM) of UCLA are the components of our coupled GCM. The AGCM provides the wind stress, heat and freshwater fluxes to the OGCM, and the OGCM returns sea-surface temperature (SST) to the AGCM (Mechoso *et al.*, 1991a). The OGCM has a Global version (Bryan and Cox, 1967; Cox and Bryan, 1984) and a Tropical Pacific version with enhanced resolution in the equatorial region (Philander and Pacanowski, 1980). They cover the ocean in the latitude belts from 60°S to 60°N and from 28°S to 50°N, respectively. The northernmost and southernmost parts of the domains are relaxed towards the observed climatology in both salinity and temperature fields. Incorporation of a sea-ice module is under way.

The AGCM has been developed under the direction of A. Arakawa, with the participation of his colleagues and students (Arakawa and Lamb, 1977). This effort has influenced similar developments around the world during the last 30 years. In the middle 1970s, a version of the model was implemented at the US Naval Environmental Prediction Research Facility and the Fleet Numerical Weather Center, both in Monterey, California. This version evolved into the operational NOGAPS (Navy Operational Global Atmospheric Prediction System) forecasting system (Rosmond 1981). The same version is extensively used for forecasting and climate studies at the Meteorological Research Institute in Tsukuba, Japan (Tokioka *et al.*, 1984).

The current version of the model has been used since the early 1980s at UCLA and Colorado State University (Randall *et al.*, 1985). The distinctive feature of this latter version is the treatment of the planetary boundary layer (PBL), which is considered well-mixed and is represented by the model's bottom layer, whose variable depth is predicted (Suarez *et al.*, 1983). The PBL parameterization is crucial for modeling heat and momentum fluxes at the ocean-atmosphere interface. Constant effort is dedicated to improvement of the finite-difference schemes and parameterizations of physical processes included in the model and to optimization of its computer code.

The coupled GCM produces a realistic simulation of the seasonal cycle (Mechoso *et al.*, 1991a), without any flux correction. Figures 4 and 5 show the simulated SST field for July, and the time series of simulated SST at the equator, respectively. Figure 4 depicts realistic configurations for the warm pool in the western Pacific and the cold tongue in the eastern Pacific. Figure 5 shows that the east-west temperature gradient is maintained throughout the year by the coupled system, with the extent of cold water largest in July. There is no evidence of significant climate drift, which is a major concern in modeling of the coupled system (Neelin *et al.*, 1992). The successful simulation of the seasonal cycle is a prerequisite for using the coupled GCM in support of our planned data assimilation and predictability studies. We plan to implement, for the OGCM, a four-dimensional data assimilation scheme based on OI and successive corrections.

The computer code of the coupled GCM is being restructured as part of our participation in the Corporation for National Research Initiatives (CNRI) Gigabit Testbed Initiative. In the final stages of this task, computations will be distributed among several supercomputers connected by a

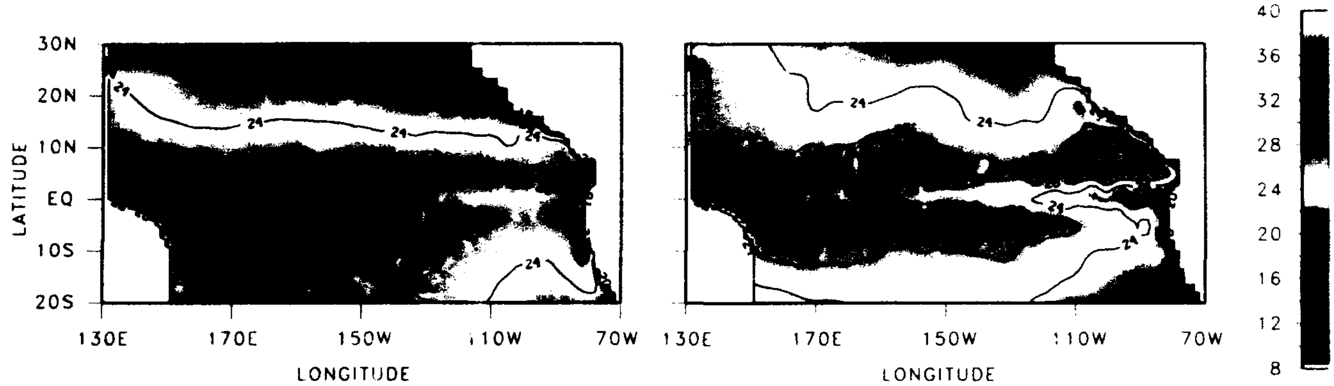


Fig. 4: Sea-surface temperature for January (left) and July (right) corresponding to year 7 in a simulation with the coupled ocean-atmosphere GCM. Units are °C. (After Mechoso et al., 1991a.)

wide-area high-speed (gigabit per second) network (Mechoso *et al.*, 1991b). Other avenues of parallelization for SIMD (single-instruction/multiple data) and MIMD (multiple-instruction/multiple data) architectures are being tentatively explored on simplified GCMs by Ghil *et al.* (1991b).

Concluding Remarks

Methodology for data assimilation and predictability studies on various time scales has been developed and tested on simple models and is ready to be implemented for the UCLA coupled atmosphere-ocean GCM. At the same time, simulations of the seasonal cycle and interannual variability with the coupled GCM are being evaluated. A number of interesting results on data assimilation and predictability for the ocean have been obtained in the process.

In the area of data assimilation, we have evaluated the relative merits of various assimilation methods for the atmosphere and oceans. We have shown the ability of the Kalman filter to track vigorous barotropic and baroclinic instabilities and of the extended Kalman filter to track regime changes in chaotic and stochastically perturbed flows. In the area of predictability, our results include the impact of physical parameterizations (such as that for radiative effects in the AGCM and vertical mixing in the OGCM) on the performance of the coupled system; the existence of shortwave instabilities in frontal structures, both near coasts and in the open ocean; and a theoretical justification of the stability of localized coherent vortex structures in the ocean.

As part of the technological basis for implementing advanced assimilation methods and performing extensive predictability studies on coupled GCMs, we also are exploring modern computer architectures and networks. We expect the coming decade to be one of great excitement for the description, understanding, and prediction of the coupled ocean-atmosphere system.

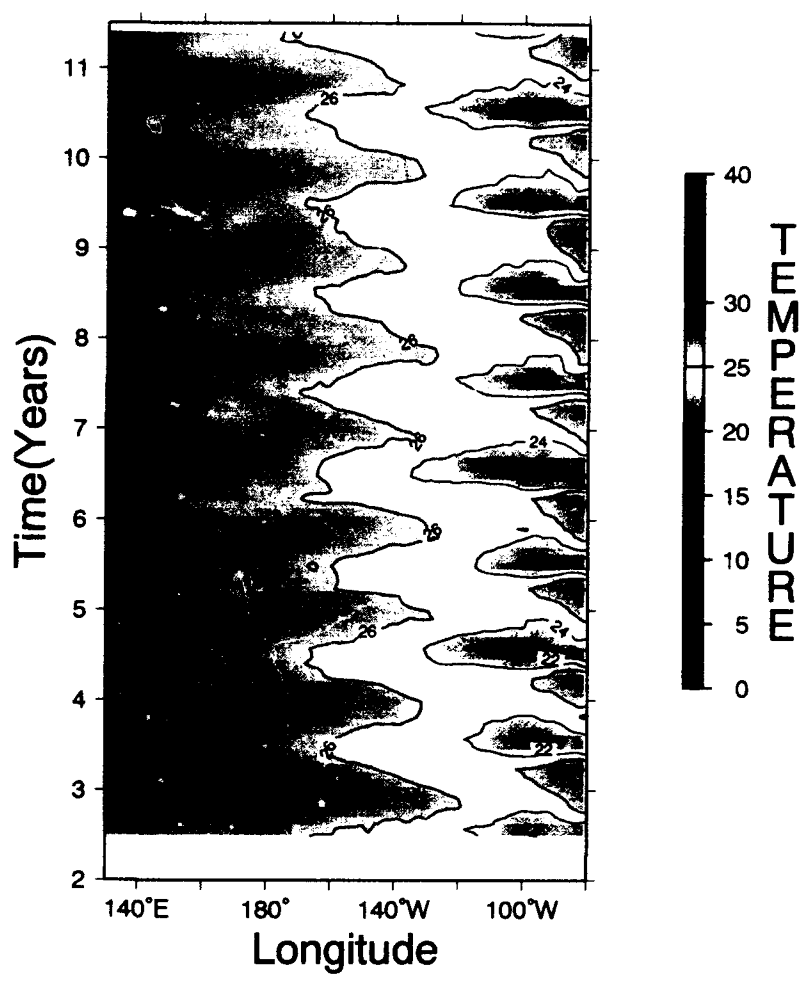


Fig. 5: Time variation of sea-surface temperature at the equator from a simulation with the coupled ocean-atmosphere GCM. Units are °C. (After Mechoso et al., 1991a.)

Acknowledgements

It is a pleasure to thank the other participants in this project: Y. Chao, Y. Feliks, M. Fisher, Z.

Hao, S. Jiang, C.-C. Ma, N. Paldor, H. Sakuma, J.A. Spahr, R. Todling, and W.M. Weibel. Many useful discussions with A. Arakawa, D. Halpern, P. Malanotte-Rizzoli, R.N. Miller, and J.D. Neelin are gratefully acknowledged. The manuscript was typed by C. Wong; Figures 1 and 2 were prepared by R. Todling, Figure 3 by Z. Hao, and Figures 4 and 5 by W.M. Weibel. This research was supported by UCAR/INO under contract S8757 and by ONR under contract N000-14-87-K-0331 and grant N00014-89J-1845. Additional support was provided by NSF under grant OCE-89-18439, NASA under grant NAG5-713, NASA/JPL under contract 958658, NIGEC under contract UCD/WESTGEC 9H12, INCOR, NSF and DARPA under Cooperative Agreement NCR-8919038 with CNRI, and by a Guggenheim Fellowship to M. Ghil.

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A Prototype Fully Coupled Ocean-Atmosphere Prediction System

By Thomas E. Rosmond

Coupling of the Navy's atmosphere and ocean prediction models has a natural place in the Navy's research mission and is a major goal of meteorologists and oceanographers in the Naval Oceanographic and Atmospheric Research Laboratory (NOARL) during the 1990s. Navy atmospheric models have been providing valuable support to Navy operations for many years, and computer power now has made operational ocean prediction models feasible.

The challenges of successfully coupling atmosphere and ocean models are great. Coupled systems must accurately predict air/sea interface conditions, e.g., sea-surface temperature (SST) and surface fluxes, whereas uncoupled atmosphere and ocean models depend on prescribed interface conditions. The extra degrees of freedom at the interface in the coupled systems may be a theoretical advantage for realistic simulation of atmosphere/ocean exchanges, but the lack of any constraints at the interface also can allow unacceptable systematic errors, e.g., SST biases. The goal of NOARL atmosphere and ocean modelers is to design atmosphere and ocean models that can exploit the advantages of coupling without the systematic errors.

For many years, there has been general consensus among meteorologists and oceanographers that two-way interactive coupling should be the best way to model the interactions between the atmosphere and ocean. Early research efforts such as Manabe *et al.* (1975) and more recently Manabe and Wetherald (1986) concentrate on longer-term climate-time-scale simulations, where atmosphere-ocean interaction is a dominant factor determining the behavior of both the atmosphere and ocean components of the coupled system. Even these efforts restrict the coupling to a simplified ocean mixed-layer model underneath an atmospheric general circulation model (AGCM). Experiments with a fully coupled AGCM and three-dimensional ocean general circulation model (OGCM) have been limited, but some early attempts have been made (e.g., Washington and Meehl, 1989; Stouffer *et al.*, 1989). Fully coupled experiments for the shorter time scales (5–10 days) of traditional numerical weather prediction (NWP) or even extended prediction (30 days) are now getting scientific attention. Experiments on the sensitivity of NWP models to SST anomalies suggest that even after 10 days, air/sea interaction effects are still minor compared with other physical processes in the free atmosphere (Ranelli *et al.*, 1985). Therefore even a perfectly interacting atmosphere/ocean model will probably show little positive benefit for the atmospheric part of the forecast. The benefit to the ocean part of the forecast, specifically the ocean mixed layer, has not been studied, however, and cannot be ignored in determining potential benefits and research priorities for fully coupled models.

. . . even after 10 days, air/sea interaction effects are still minor compared with other physical processes . . .

The coupled Navy Operational Global Atmospheric Prediction System/Thermodynamic Oceanographic Prediction System (NOGAPS/TOPS) is the Navy's first effort at joining an AGCM/NWP model and an ocean mixed-layer model such as TOPS. The choice of NOGAPS and TOPS is a clear one because each is a well-established operational system in its own right, and there is abundant expertise available for both at NOARL and Fleet Numerical Oceanography Center (FNOC). The documented performance records of each of the operational systems also provide excellent control data for coupled system evaluation and validation.

The Coupling Problem

Atmosphere/ocean systems coupling strategies are of two types.

Asynchronous or Loosely Coupled

The two models of the system run in sequence, each model getting forecast time-series forcing fields from a previously run sequence of the other model. Typically the atmospheric model is run for a 24-hour forecast with a fixed SST as the bottom boundary condition. The ocean model then runs for this same 24 hours being forced by the time series (e.g., every 3 hours) of surface fluxes

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generated by the atmospheric model over the period. At the end of the 24 hours, the ocean model has predicted a new SST, and the atmospheric model can begin another cycle.

Synchronous or Tightly Coupled

The two models are integrated in lockstep, exchanging the SST and surface flux information at the same grid points for every model time step. There is now only one combined model, the interactions across the air/sea interface being modeled in more detail than in the loosely coupled case.

Another serious problem with coupled atmosphere/ocean models is the development of large systematic errors . . .

Readers may feel that there is little fundamental difference between these two approaches, only a different time step separating exchange of information across the air/sea interface. Logistically, however, the loosely coupled system is more easily controlled because the exchange of parameters across the models' air/sea interface is independent of the time integration processes of the models. Typically the parameters are stored in a data base where they can be subjected to filtering, various kinds of quality control, and other reality checks before being passed to the appropriate model component. Figure 1 shows the asynchronously coupled system of NOGAPS and TOPS currently run operationally by FNOC. The combined systems do four-dimensional data assimilation for

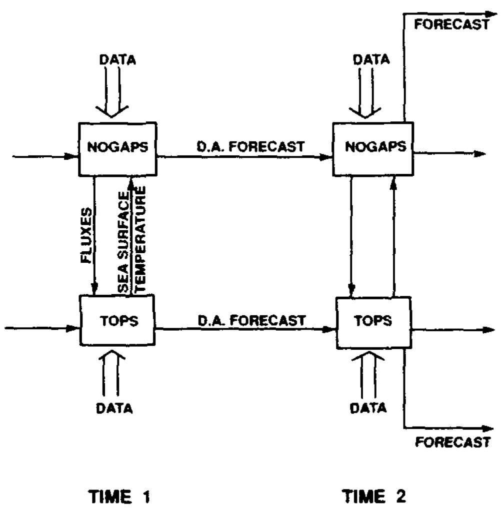


Fig. 1: The loosely coupled atmosphere/ocean data assimilation (D.A.) system of NOGAPS and TOPS currently runs operationally at Fleet Numerical Oceanography Center. The horizontal arrows between the boxes are the short D.A. forecasts; the arrows at the upper and lower right corners are longer forecasts. For simplicity the D.A. forecasts are shown to be the same length in both NOGAPS and TOPS, typically however, a TOPS D.A. forecast is 24 hours and a NOGAPS D.A. forecast is 6 hours.

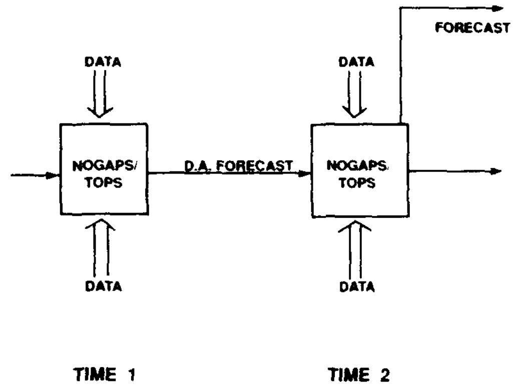


Fig. 2: The fully coupled (synchronous) NOGAPS/TOPS system. The boxes represent analysis times, when observations from both the atmosphere and ocean are assimilated. The arrows between boxes are the short data assimilation (D.A.) forecasts, and the arrow on the upper right is a longer forecast periodically spun off.

both the atmosphere and ocean. The interval between oceanic data insertion is 24 hours and for atmospheric data is 6 hours. The TOPS SSTs and NOGAPS surface fluxes are subject to climatological adjustments to prevent large biases from developing in the models' forecasts.

The fully coupled NOGAPS/TOPS that is the subject of this report is an example of a synchronously coupled system. Figure 2 shows the intimate relationship of the two models, and Figure 3 demonstrates the vertical layer structure on each side of the air/sea interface. The TOPS SST is fed to NOGAPS and the NOGAPS fluxes of momentum, sensible heat, latent heat (evaporation), and precipitation are fed back to TOPS. Instead of a data-base interface between the two models, all exchange of these parameters is done internal to the models through the memory of the host computer system. The ability to apply quality control and other constraints is limited compared with the loosely coupled case (Fig. 1). Furthermore, the short time interval of parameter exchange (typically 15- to 20-minute steps) sometimes allows the development of spurious high-frequency solution modes (e.g., high-amplitude inertial oscillations) that are difficult to eliminate and can contaminate physically realistic solutions. The many hours between parameter exchange and data insertion in the loosely coupled system effectively filter high-frequency modes and prevent this contamination.

Another serious problem with coupled atmosphere/ocean models is the development of large systematic errors or biases in the models' solutions. These errors are often called "climate drift" and are common to all AGCMs, whether coupled to ocean models or not. For coupled models, sys-

tematic errors in AGCM surface fluxes are most critical. As mentioned above, the loosely coupled operational NOGAPS/TOPS depends upon climatological constraints on the surface fluxes to prevent the predicted SST from developing large biases in areas where NOGAPS fluxes are in error. NOGAPS surface-flux systematic errors, although no worse than those of other major AGCMs, are still too large to allow unconstrained air/sea interactions. In fact, no AGCM is yet good enough to satisfy this demand (Schneider, 1990). The great challenge for fully coupled NOGAPS/TOPS research and development is to reduce surface-flux systematic error so that such adjustments are unnecessary.

Both loosely coupled and tightly coupled atmosphere/ocean model systems have important roles to play in the design of future Navy prediction systems. Operational-coupled AGCM/OGCMs will probably be loosely coupled, because of the large difference in time and space scales of interest. The baroclinic eddies and current systems in the ocean have time scales of order weeks and space scales of order 100 km; comparable scales in the atmosphere are days and 1,000 km. For these time and space scales, all interaction of interest takes place over the time scales that are well resolved by the data insertion interval of four-dimensional data assimilation (12/24 hours). However, fully coupled AGCM/OGCMs certainly do have a place for seasonal and multiple-year model integrations. Simulating the subtle interactions between atmosphere and ocean that are of such great importance for questions of global climate change may only be captured by a closely coupled AGCM/OGCM. In the future, such a model will be an important part of the Navy's research on air/sea interaction and model systematic error reduction.

On the other hand, tightly coupled AGCMs and ocean mixed-layer models, such as NOGAPS/TOPS, are appropriate because the important time and space scales of the atmosphere and ocean mixed-layer are quite comparable. Surface fluxes drive the mixed layer, and responses in the form of mixed-layer deepening and inertial oscillations can occur within hours after the passage of intense cyclones and frontal systems. Only a tightly coupled system can faithfully capture these kinds of interactions.

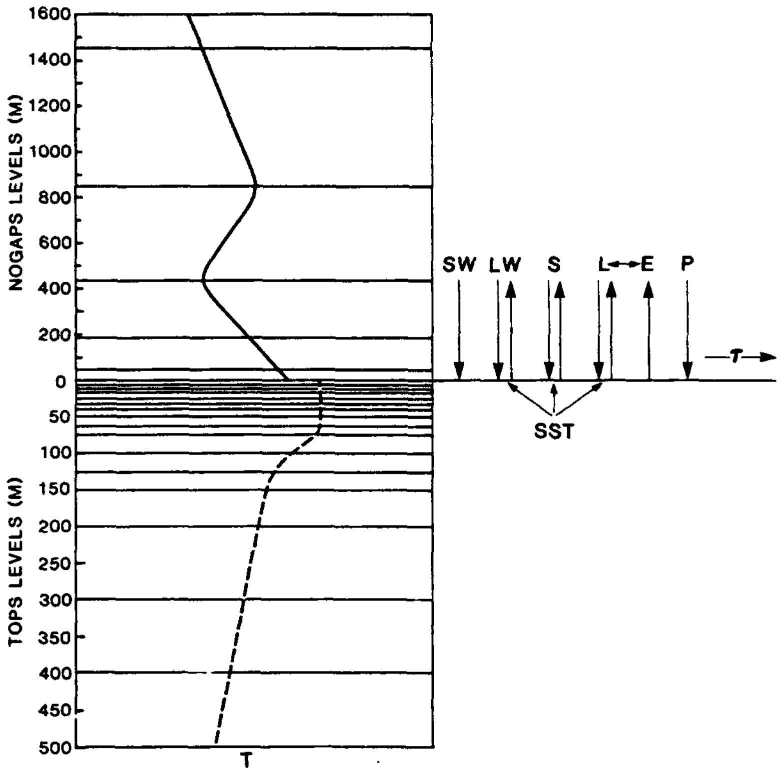


Fig. 3: The vertical structure of the coupled NOGAPS/TOPS system. Exchanges of sea-surface temperature and the fluxes of heat [sensible (S), latent (L), shortwave (SW), and longwave (LW) radiation], moisture evaporation (E) and precipitation (P), and friction (τ) take place at the air/sea interface. Idealized profiles of temperature (T) in the planetary boundary layer and mixed layer are shown. Note that the vertical scales on each side of the interface are not the same.

Description of Navy Operational Global Atmospheric Prediction System

The NOGAPS forecast model is a highly sophisticated AGCM, similar in design and performance to the NWP models run operationally at the European Centre for Medium-Range Weather Forecasts (ECMWF) and at the National Meteorological Center (NMC). A description of NOGAPS and a summary of operational performance is given by Hogan and Rosmond (1991). More details of the NOGAPS spectral forecast model are given in Hogan *et al.* (1991). Only a brief summary will be given here.

NOGAPS is actually much more than a forecast model. It is a complete atmospheric forecast system, capable of assimilating atmospheric observations of all types, including satellite data, and capable of producing a wide variety of physical parameters used in all of FNOC's applications supporting fleet operations. NOGAPS checks all observations with elaborate objective quality control (Baker, 1991) before using these data in a global optimum-interpolation objective analysis (Barker *et al.*, 1988). Undesirable gravity waves are filtered from the analysis fields with nonlinear normal-mode initialization (Hogan *et al.*, 1991). The NOGAPS forecast model is spectral, with an operational horizontal resolution of 1.5 deg and 18 vertical layers from the surface to 10 millibars. The model contains the physical processes of the planetary boundary layer (PBL), gravity-wave drag, cumulus convection, stable precipitation,

NOGAPS [Navy Operational Global Atmospheric Prediction System] is . . . a complete atmospheric forecast system . . .

short- and longwave radiation, and ground hydrology.

Every component of a system like NOGAPS is important because there are complex interactions taking place among all physical processes, just as in the real atmosphere. However, for the coupling problem there are special areas of emphasis.

PBL Parameterization

This computes the surface fluxes that ultimately drive TOPS. The NOGAPS PBL is similar to that used by ECMWF (Louis *et al.*, 1982). An important NOGAPS modification to the basic PBL parameterization scheme is a shallow cumulus (e.g., trade-wind cumulus) parameterization that enhances surface fluxes when the PBL is conditionally unstable.

Cumulus Parameterization

This is based on the Arakawa-Schubert scheme (Hogan *et al.*, 1991). In the tropics the interaction of cumulus convection with the PBL is the dominant factor in determining surface-flux distributions. No AGCM can predict realistic surface fluxes unless cumulus/PBL interactions are adequately simulated. Great effort has gone into the design and "tuning" of the NOGAPS cumulus and PBL parameterizations to achieve this.

Radiation/Cloud Interactions

This is probably the single most important factor in determining AGCM systematic error properties. Sensitivity experiments with NOGAPS have demonstrated that interaction of solar and infrared radiation with clouds dominates the global heat budget. The vertical distribution of radiative heating determines atmospheric stability and therefore the distribution and intensity of cumulus convection, which in turn interacts with the PBL to influence the surface fluxes. Success in coupled atmosphere/ocean modeling, and specifically the coupled NOGAPS/TOPS, will largely depend on proper representation of the global cloud field and its interaction with the NOGAPS radiation parameterizations. For a description of the NOGAPS radiation see Hogan *et al.* (1991).

. . . interaction of solar and infrared radiation with clouds dominates the global heat budget.

No significant changes are made to the formulation of the operational version of NOGAPS for the coupled NOGAPS/TOPS configuration. However, TOPS computer memory requirements added to operational NOGAPS requirements exceed the limits of the FNOC computer system, so the coupled NOGAPS/TOPS is run with a 20% reduction in horizontal resolution compared with the operational NOGAPS.

The only manifestation of the interaction with the ocean mixed layer is the time-dependent SST instead of the time-invariant SST normally used when NOGAPS is run operationally. In NOGAPS, the SST is carried as part of the global surface temperature field. This is already a predicted quantity for land areas, so it is trivial to allow the SST to vary also.

Description of Thermodynamic Ocean Prediction System

Clancy and Pollak (1983) describe TOPS, the ocean mixed-layer component of the coupled NOGAPS/TOPS system. The operational TOPS runs daily at FNOC as part of a global ocean data assimilation and forecast system. TOPS itself is only the forecast component; the Optimum Thermal Interpolation System (OTIS), described by Clancy *et al.* (1990), is the analysis component. SST, mixed-layer thickness, and vertical density profiles are among the parameters produced by the TOPS/OTIS-based system. OTIS is external to the coupled NOGAPS/TOPS, as is the equivalent atmospheric analysis component (Barker *et al.*, 1988), and so is not discussed here.

TOPS is based on the higher-order turbulence closure theory following Mellor and Yamada (1974). The operational TOPS corresponds to a level-2 closure in the Mellor/Yamada hierarchy. In this closure, a local balance between generation and dissipation of turbulent kinetic energy (TKE) is assumed. From this balanced TKE distribution, eddy mixing coefficients are derived, allowing the computation of vertical turbulent mixing in the mixed layer.

The governing equations of TOPS predict vertical mixing of heat and salinity and also the Ekman component of the horizontal momentum field. There is no explicit modeling of the geostrophic component of the momentum. This must be externally specified from climatological sources or, eventually, from a loosely coupled OGCM.

Some modifications of the original operational TOPS are made for the coupled NOGAPS/TOPS version.

1. The TOPS forecast grid is modified to correspond to the global latitude/longitude grid of NOGAPS; the operational TOPS runs on separate polar stereographic forecast grids for the northern and southern hemispheres.
2. The model runs as a set of FORTRAN subroutines called by NOGAPS, rather than as a stand-alone program. This allows the easy exchange of SST and surface fluxes across the air/sea interface of the two model components.
3. The assumption of balance between production and dissipation of TKE is relaxed in the coupled NOGAPS/TOPS. Numerical experiments show that for intense, rapidly moving atmospheric frontal systems, production of TKE in the mixed layer is significantly greater than dissipation for a few hours in the areas directly influenced by the front. An implicit time-integration scheme allows an imbalance to exist when surface forcing is strong, but quickly returns the mixed

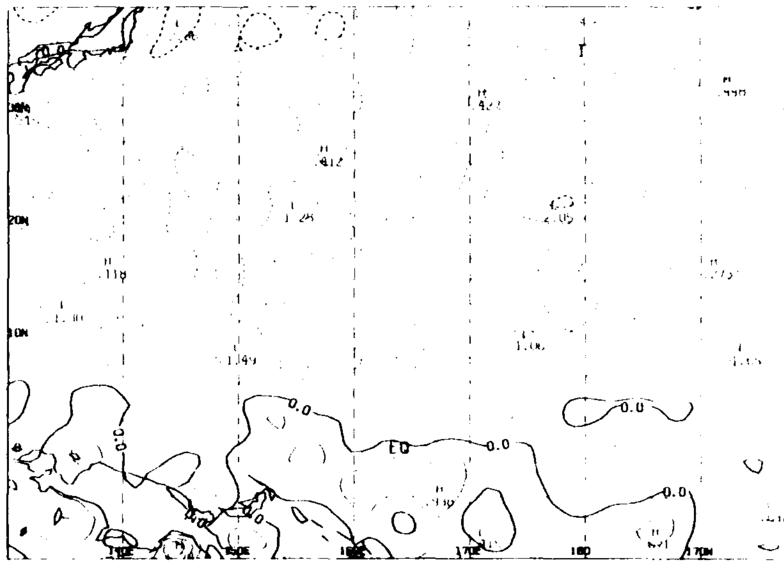
layer to a balance when the transient forcing passes. Numerical problems such as spurious high-amplitude inertial oscillations are suppressed by this TOPS modification.

Fully Coupled Model Results

The coupled NOGAPS/TOPS has been run for several 10-day forecast case studies and some 30-day extended forecast experiments. A comprehensive discussion of research results is beyond the scope of this report. The following observations summarize the coupled system's performance.

1. A general SST cooling bias over the winter-hemisphere ocean basins is observed. SST cooling biases also occur in some tropical regions.
2. Global mean sensible and latent heat fluxes between the atmosphere and ocean are systematically reduced in the coupled NOGAPS/TOPS compared with control experiments where SST is prescribed. This implies reduced air/sea temperature differences, consistent with an SST cooling bias.
3. The meridional Hadley circulation in NOGAPS is slightly weakened, suggesting reduced tropical convection. This is consistent with cooler tropical SSTs.

As an example of the coupled systems performance, a NOGAPS/TOPS 10-day SST forecast change (Fig. 4A) and the actual observed change (Fig. 4B) are presented. The plotted area, extracted from the global forecast domain, is the western Pacific during late January, 1991. The model captures the overall cooling outside the tropics and also the warming south of the equator, although details are poorly predicted and the cooling is predicted to be greater than observed, consistent with the global bias. In the area of the Kuroshio current south of Japan, the observed change shows some warming and cooling areas, totally absent in the prediction, which are due to meanders in the Kuroshio. NOGAPS/TOPS was run without a geostrophic current component for this case and so cannot capture this effect. Only a coupled OGCM can provide the current variability.



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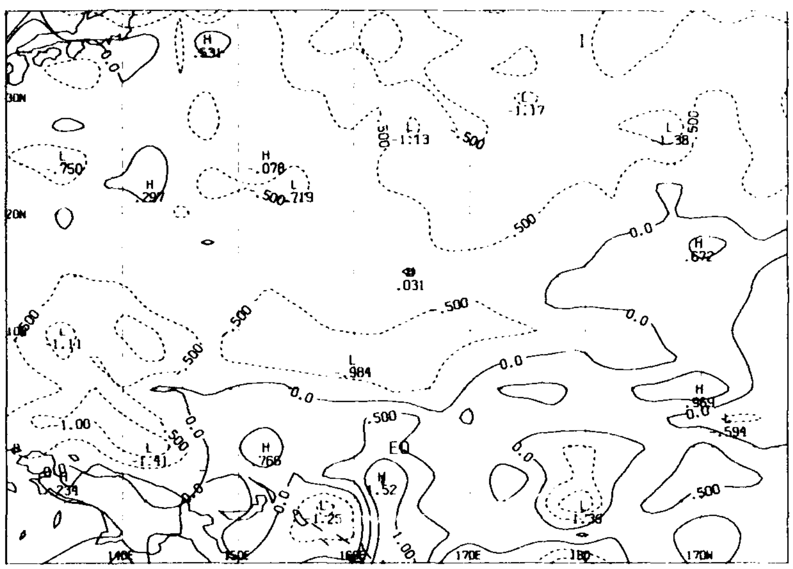

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Fig. 4: (A) Ten-day NOGAPS/TOPS predicted change of sea-surface temperature in the western Pacific (valid 1200 GMT, 27 January 1991). Units are °C. (B) Ten-day observed change of sea-surface temperature in the western Pacific for same period as in A (valid 1200 GMT, 27 January 1991). Units are °C.

Summary

A pessimistic interpretation of the results shown in the previous section is tempting, but premature. The coupled NOGAPS/TOPS has shown itself to be an extremely sensitive indicator of systematic errors and therefore an excellent research tool for the reduction of these biases. Coupled model results have contributed to several NOGAPS changes that reduced the systematic error. Although most of the research and testing for these improvements did not use the coupled NOGAPS/TOPS directly, the impact of the changes on the coupled system is an important test. Reduction in systematic error improves all applications dependent on NOGAPS, and the operational TOPS/OTIS particularly benefits from better surface fluxes. Therefore, though the fully coupled NOGAPS/TOPS is not yet a competitive alternative to the present loosely coupled systems, it is already an important contributor to overall progress in coupled model development. Navy operations are benefiting from improvements in NOGAPS and TOPS. The goal of an operational fully coupled NOGAPS/TOPS is the ultimate

prize of current research efforts, but the benefits derived along the way are also important.

Acknowledgements

This research is supported by the Office of Naval Research, Navy Ocean Modeling and Prediction (NOMP) program, project element 62704N, R.A. Peloquin, Program Manager. NOARL contribution no. 432:078:91. Approved for public release; release is unlimited.

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OPERATIONAL MODELING: OCEAN MODELING AT THE FLEET NUMERICAL OCEANOGRAPHY CENTER

By R. Michael Clancy

REFLECTING the organization's growing responsibilities and capabilities in oceanography, ocean modeling, and coupled air-sea modeling, Fleet Numerical Weather Central, Monterey, was redesignated as the Fleet Numerical Oceanography Center (FNOC) in 1979. In addition to being a world-class global weather prediction center, FNOC is now widely regarded as the leading source of operational oceanographic information in the world. Indeed, it is this emphasis on oceanography that distinguishes FNOC from all other operational weather prediction centers. No other center has FNOC's responsibility for predicting the global environment from the top of the stratosphere to the bottom of the ocean, and no other center has as complete an air-sea data base.

FNOC operates around the clock, 365 days a year, providing services to United States and allied naval forces, other components of the Department of Defense, and a broad spectrum of civilian interests. The center operates a sophisticated suite of numerical oceanographic and atmospheric models and satellite processing software in a multi-mainframe supercomputer environment. Products are distributed to users around the world, both ashore and afloat, through a variety of communications networks.

In general, accurate representation of oceanic physics, data assimilation, and coupling with atmospheric models via air-sea heat and momentum fluxes are major issues associated with the ocean models in use at FNOC. Research and development (R&D) support for these models is coordinated through the Navy Ocean Modeling and Prediction (NOMP) program. The supporting R&D is performed mainly by the Oceans and Atmosphere Directorate of the Naval Research Laboratory (NRL). A formal and highly structured process exists for making the transition of models from R&D at NRL into operations at FNOC.

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FNOC's emphasis on treating the global atmosphere and ocean as a coupled system makes its operational models and data bases important national resources for monitoring and studying climate and global change. Largely because of this, the National Oceanic and Atmospheric Administration (NOAA) established the Center for Ocean Analysis and Prediction (COAP) in collocation with FNOC in 1988. COAP facilitates civilian access to FNOC air-sea products and fosters their use in a wide range of research applications.

Operational Use of Ocean Models

More than a dozen ocean model systems run operationally at FNOC (Clancy, 1987; Clancy and Sadler, 1992). Some run on global grids with relatively coarse spatial resolution, and others function on limited-area grids with fine-scale spatial resolution applied in geographical areas of particular Navy interest. All of the ocean models are fully automated and operated on a fixed schedule, with most run once per day. The hardware, software, data base, communications, and manpower infrastructure necessary to support operation of these models overlaps substantially and naturally with that required to support the weather prediction models in use at the center.

More than a dozen ocean model systems run operationally at FNOC [Fleet Numerical Oceanography Center]

The FNOC ocean models fall into three general categories: thermal structure and circulation, sea ice, and sea state. The thermal-structure and circulation models depict ocean fronts and eddies and provide input to acoustic models, which predict the performance of the Navy's acoustic sensors. In addition, they provide the sea-surface temperature (SST) boundary condition for atmospheric models, and predict surface currents in support of ocean search and rescue and optimum-track ship routing. The sea-ice models predict ice thickness, concentration, and drift in support of the Navy's arctic operations. Finally, the sea-state models predict directional wave-energy spectra, from which wave height, period and direction fields are derived in support of ship routing and a variety of other activities.

. . . the models augment . . . *in situ* oceanographic data . . . by inferring oceanographic information from other sources.

Emphasis is placed on using the ocean models to convert well-observed surface oceanographic or atmospheric information into an accurate representation of oceanographic fields for which observations are sparse or nonexistent. For example, the surface positions of fronts and eddies observed by satellites are used to map subsurface salinity and thermal structure via synthetic data and ocean-feature models in the Optimum Thermal Interpolation System Version 3.0 (OTIS 3.0) analysis (Cummings and Ignaszewski, 1991). Surface wind stresses and heat fluxes provided by FNOC atmospheric models are used to predict mixed-layer depth and surface currents via the vertical mixing parameterizations in the Thermodynamic Ocean Prediction System (TOPS) model (Clancy and Pollak, 1983). This atmospheric forcing is also used to predict ice thickness and drift via the dynamics and thermodynamics in the Polar Ice Prediction System (PIPS) model (Preller and Posey, 1989). Finally, surface winds and wind stresses from the atmospheric models are used to predict directional wave-energy spectra via the wave physics in the Global Spectral Ocean Wave Model (GSOWM) (Clancy *et al.*, 1986) and the third-generation wave model (WAM) (WAMDI Group, 1988). Thus, the models augment the extremely sparse *in situ* oceanographic data in a substantial way by inferring oceanographic information from other sources. Through these sophisticated processes, the models are able to provide a much more accurate and complete representation of the ocean than could be obtained from either oceanographic climatology alone, real-time oceanographic data alone, or a simple combination of the two.

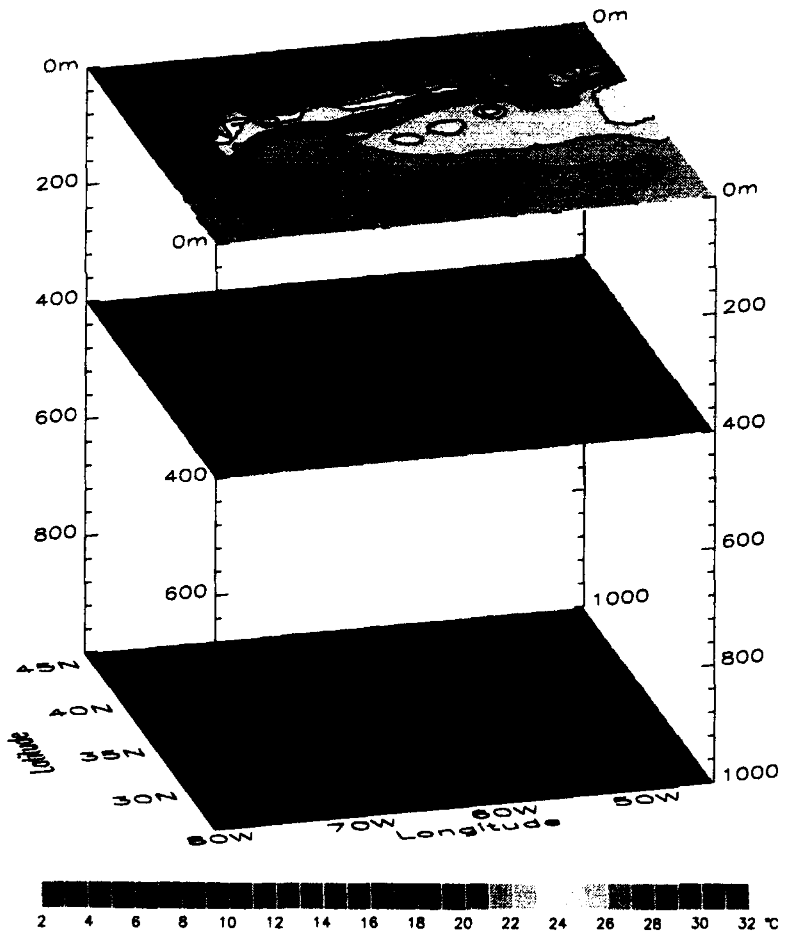

Fig. 1: Temperature at 0, 400, and 1,000 m depth in the Gulf Stream region from Version 3.0 of the Optimum Thermal Interpolation System (OTIS) model on 26 July 1991. The contour interval is 1°C, and the color bar indicates temperature ranges in °C.

Example Output

The OTIS 3.0 ocean thermal model (Cummings and Ignaszewski, 1991; Clancy *et al.*, 1991) generates synthetic subsurface data from the surface positions of fronts and eddies observed in satellite imagery and a water-mass–based representation of historical bathythermograph data. Used in conjunction with "ocean-feature models," which describe the transition between water masses across frontal boundaries, and the optimum-interpolation data-assimilation technique, these synthetic data allow OTIS 3.0 to produce a rather accurate three-dimensional analysis of the ocean mesoscale. An example is presented in Figure 1, which shows the temperature at 0, 400, and 1,000 m produced by OTIS 3.0 in the Gulf Stream region on 26 July 1991. The subsurface representation of the Gulf Stream front and associated eddies evident in the figure could not be derived from available *in situ* data. It is a direct result of the model's translation of surface information (satellite-observed surface positions of features) into subsurface information (synthetic subsurface data). Note that several of the features in Figure 1 exhibit stronger horizontal temperature gradients at depth than at the surface, which is characteristic of summertime conditions in this region.

The PIPS sea-ice model (Preller and Posey, 1989; Preller, 1992, this issue) is based on the formulation of Hibler (1979) and contains a sophisticated treatment of ice dynamics and thermodynamics. Ice thickness and drift from the basin-scale PIPS model for 1 March 1990 are shown in Figure 2. Vigorous cyclonic ice drift, driven by a strong atmospheric low-pressure system, is present in the eastern arctic, while the central and western arctic are relatively quiescent. The model predicts the thickest ice along the Canadian Archipelago, with relatively thin ice along the ice edge and in the Kara and Barents Seas. The detached circular region of thin ice off the northeast coast of Greenland is the seasonally recurring "Odden" feature (Vinje, 1983), which reflects the circulation in the Greenland Sea Gyre.

The GSOWM sea-state model (Clancy *et al.*, 1986) is based on the linear "first-generation" wave physics of Pierson (1982). An example of GSOWM output is shown in Figure 3, which depicts a directional wave-energy spectrum predicted by the model at a point in the northwest Atlantic during the Labrador Extreme Waves Experiment (LEWEX). This bimodal spectrum reflects propagation of swell from the northwest and windsea from the east. The swell energy is dying while the sea energy is growing in response to a 17 m s^{-1} easterly wind. The height, period, and direction derived from the model spectrum are 4.4 m, 10 s, and 86° for the sea and 2.5 m, 11 s, and 334° for the swell. The significant wave height derived from the model spectrum is 5.0 m.

Model Validation

A model undergoes a formal and sometimes lengthy Operational Test (OPTEST) before it is accepted for operational use. The primary purpose of the test is to demonstrate that the model runs reliably in the operational jobstream and produces a useful product from operationally available data inputs. Generally a model under OPTEST is intended to replace an existing operational model, and in these cases it also must be demonstrated that products from the new model are an improvement over those provided by the old model.

A wide variety of data are used for validation. For example, the ocean thermal and circulation models are validated with bathythermograph, satellite Multi-Channel Sea Surface Temperature (MCSST) and ship data (Clancy *et al.*, 1990, 1992), and drifting buoy data (deWitt *et al.*, 1989). The sea-ice models are validated with drifting buoy data, submarine ice-thickness data, and analyses of ice concentration and drift derived from satellite data (Preller and Posey, 1989; Fett, 1990; Emery *et al.*, 1991). The sea-state models are validated with buoy, ship, and satellite altimetry data (Clancy *et al.*, 1986; Pickett *et al.*, 1986; Rao, 1989; Wittmann and Clancy, 1991a,b).

An example of ocean-thermal-model validation is shown in Figure 4. This figure shows a 2-month time series of root-mean-square (rms) errors for the FNOC regional SST field in the western North Atlantic. It is based on comparison of approximately four to six bathythermograph observations made in the region each day with the previous day's analyzed SST field (thus, the SST validated on each day is independent of the validation data). During the first 29 days of the period (red curve), the SST field was produced by the OTIS 2.0 model, and the rms error averaged about 2.2°C. The more advanced OTIS 3.0 model (Cummings and Ignaszewski, 1991) was implemented on 30 August 1990, and the resulting rms errors (blue curve) reflect this improvement, averaging only about 1°C during the last 30 days of the record.

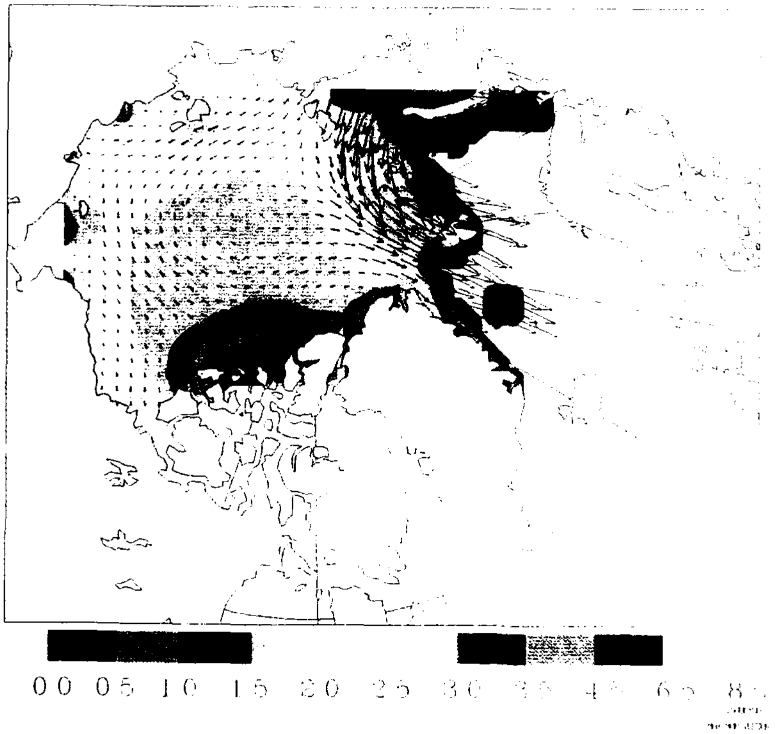

Fig. 2: Ice thickness (color) and ice drift (vectors) from the Polar Ice Prediction System (PIPS) model on 1 March 1990. The color bar indicates ice thickness ranges in meters, and the reference vector at the lower right corner defines ice drift of 0.5 m s^{-1}.

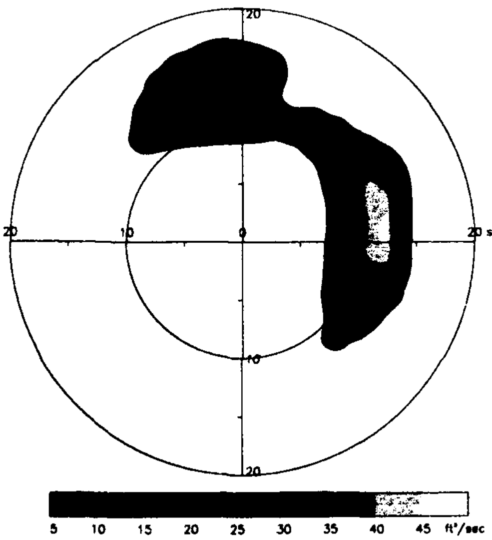

Fig. 3: Directional wave energy spectrum from the Global Spectral Ocean Wave Model (GSOWM) for 50.0°N, 47.5°W at 1200 GMT, 13 March 1987. Azimuth indicates the direction from which wave energy is coming and radius gives the wave period in seconds. The color bar indicates wave energy ranges in ft^2 s^{-1}.

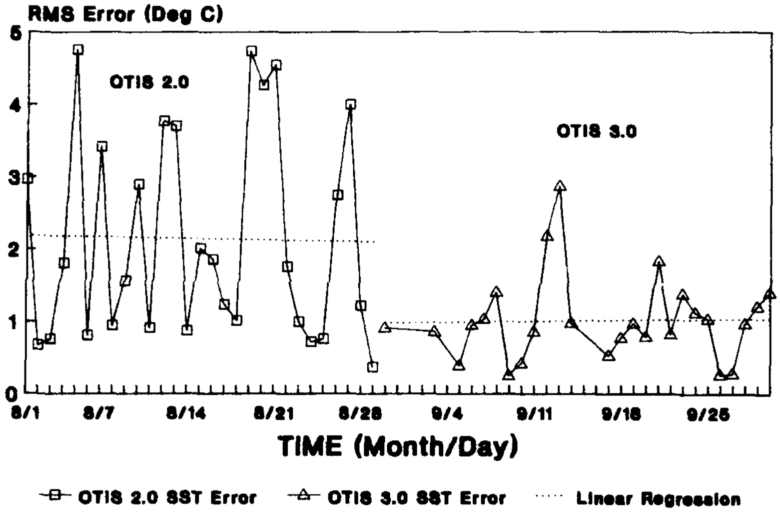

Fig. 4: Time series of root-mean-square errors for the Fleet Numerical Oceanography Center (FNOC) regional sea-surface temperature field in the western North Atlantic (26–46°N, 50–80°W) from 1 August through 30 September 1990 based on comparison of daily model-analyzed fields with unassimilated bathythermograph data. Errors for Versions 2.0 and 3.0 of the OTIS model are shown in red and blue, respectively. The least-squares regression lines through the two error curves are shown as dotted black lines.

Parallel runs of OTIS 2.0 and 3.0 using exactly the same data inputs for an earlier time period also confirm the improvement provided by the new model (Clancy *et al.*, 1991).

Summary and Outlook

FNOC has provided real-time oceanographic products to the US Navy for over 25 years and currently operates many numerical ocean models. These models are fully automated, operated on a fixed schedule, and characterized by close, and in some cases weakly two-way interactive, coupling with atmospheric models.

Most of the ocean models at FNOC run on a Cyber 205 computer, which is currently at full saturation and beyond the end of its planned life cycle. A Cray Y-MP C90 supercomputer will be installed at FNOC in 1992 to replace the Cyber 205. The speed and memory afforded by this new machine will allow major advances in the center's ocean prediction capabilities. Specifically, the OTIS thermal-analysis model, the TOPS mixed-layer model, and ocean-circulation models under development through the NOMP Program will be fully coupled with one another and run on eddy-resolving grids with basin-scale and, eventually, global-scale coverage. Assimilation of sea-surface-height data from satellite altimeters will then become a key issue in the resulting global eddy-resolving ocean-prediction system (Hurlburt, 1984). The spatial resolution of the basin-scale PIPS ice model will be increased to allow accommodation of mesoscale wind patterns, and it will be coupled with an underlying ocean-circulation model to achieve a better representation of ocean currents and ice-ocean heat fluxes in the arctic. The WAM wave model will be implemented to achieve global application of its advanced third-generation physics at a spatial resolution of 1° latitude by 1° longitude or finer. Higher-resolution regional versions of WAM will be coupled with surface currents provided by the ocean thermal-structure and circulation models to account for wave-current interactions, often important in damaging wave events. In addition, techniques will be implemented to assimilate synoptic wave data from a variety of sources directly into WAM.

A Cray Y-MP C90 supercomputer will be installed at FNOC [Fleet Numerical Oceanography Center] in 1992 . . .

By the late 1990s, the ocean thermal, sea-ice, and wave models will be merged into the global atmospheric model at FNOC to produce a software-integrated, fully coupled, and two-way interactive air-sea model. By coupling the ocean and atmospheric models in this manner, exchange of boundary-condition information between the models at every time step and joint air-sea data assimilation will be possible, leading to a more accurate representation of air-sea heat and momentum fluxes. This will improve modeling of conditions near and on either side of the air-sea interface (where the majority of critical Naval operations occur) and contribute to the extension of numerical atmospheric and oceanographic forecast skill.

The resulting real-time air-sea products from FNOC will provide both direct and indirect support of the third-generation Tactical Environmental Support System [TESS (3)], which will be deployed on the Navy's major combatants and at selected shore sites in the early 1990s. These products, highly compacted for efficient communication (Garthner *et al.*, 1991), will supply first-guess fields, initial conditions, boundary conditions, and synthetic data for local-scale models run on TESS (3). By complementing its global-scale and regional-scale mainframe-class models at FNOC with local-scale workstation-class models on TESS, the Navy will achieve an accurate, responsive, and survivable configuration for its overall environmental prediction support system.

Although FNOC's primary responsibility is to support Naval operations, its oceanographic products can contribute to the fulfillment of broader national requirements (National Research Council, 1989). For example, as a global operational air-sea prediction center, FNOC carries out global environmental monitoring on a routine daily basis. The advances in ocean modeling discussed above will enhance further this global monitoring capability by providing an improved framework for assimilating and interpreting global oceanographic data. In particular, the ocean

models expected to be operational at FNOC in the mid- to late 1990s will provide the means to assimilate satellite altimetry data into a complete depiction of the ocean mesoscale, which may be an important contributor to the global heat balance.

Acknowledgements

The contributions of the following personnel to the Oceanography Program at FNOC are gratefully acknowledged: Jim Cummings, Webb deWitt, Andy Hergert, Mark Ignaszewski, Paul May, Bruce Mendenhall, Tom Pham, Ken Pollak, Pete Tunnicliffe, and Paul Wittmann. Special thanks to Ruth Preller, Paul May, and Paul Wittmann for providing Figures 1–3.

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. . . models . . . will provide the means to assimilate satellite altimetry data into a complete depiction of the ocean mesoscale . . .

OCEAN PREDICTION AND THE ATLANTIC BASIN: SCIENTIFIC ISSUES AND TECHNICAL CHALLENGES

By J. Dana Thompson, Tamara L. Townsend, A. Wallcraft and W.J. Schmitz, Jr.

"Prediction is hard, especially about the future."
Nils Bohr

The Gulf Stream System has been a central focus for oceanography since the time of Ben Franklin and packet ships.

THE ATLANTIC is the best observed and most studied of the ocean basins. The Gulf Stream System has been a central focus for oceanography since the time of Ben Franklin and packet ships. In the North Atlantic, ocean science has been vigorously pressed to improve observations and basic understanding for the practical benefits of commerce and strategic concerns. Demands for ocean "nowcasts" (the current state of the ocean) and forecasts on time scales from the mesoscale (10s of km, days to weeks) to the basin and global scale (1,000s of km, months to decades) originate from an extraordinarily diverse community, including scientists planning and undertaking field programs, designers of new observing systems, military strategists, commercial interests, protectors of the environment, and those concerned with regional climate prediction and global change.

In the Navy Ocean Modeling and Prediction (NOMP) Program the Atlantic has served as the first test bed for research and development of limited-area ocean-forecast capabilities and their transition to an operational system (initially in the Gulf Stream from Cape Hatteras to the Grand Banks). This area has historically been of high priority for naval operations. Sponsored research by the Office of Naval Research (ONR), the National Science Foundation (NSF), other government agencies, and the international community have focused on the Gulf Stream and Northwest Atlantic for several decades [e.g., The Mid-Ocean Dynamics Experiment (MODE, POLYMODE), The Regional Energetics Experiment (REX), The Synoptic Ocean Prediction Program (SYNOP)]. As a consequence, the basic scientific understanding and data bases are *relatively* good (by oceanographic standards) for that portion of the Atlantic basin. (Compared with the atmosphere, however, the data availability is quite poor.) Nevertheless, the task of developing skillful, validated mesoscale ocean predictions, even in this limited-domain, is a stunningly difficult task. The lack of a synoptic observing network similar to that in the atmosphere is a major obstacle to success.

The essential elements for successful ocean prediction are described in various portions of this special issue and have been succinctly discussed by Hurlburt (1984) and in the *Proceedings of the Ocean Prediction Workshop* (1986). Table 1 indicates the various classes of ocean response to atmospheric forcing and provides a convenient nomenclature for the present discussion. We are attempting to forecast for all classes on the basin scale, but the primary emphasis is on Class II: mesoscale instabilities not directly forced by surface wind and heat fluxes. Three essential requirements for successful predictions are 1) adequate input data for initial and boundary conditions, as well as for validation; 2) adequate computational capability for analysis, assimilation, and prediction; and 3) properly designed and tested ocean models and assimilation schemes consistent with the available data.

A whole series of basic scientific and technical questions arise in undertaking ocean prediction

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Table 1
Classes of oceanic response to atmospheric forcing*

CLASS	EXAMPLE	IMPLICATIONS
1. STRONG, RAPID (LESS THAN A WEEK), AND DIRECT	UPPER MIXED LAYER, SURFACE WAVES, UPWELLING (BOTH COASTAL AND EQUATORIAL PROCESSES), STORM SURGES	FORECASTS ARE SHORT RANGE; LIMITED BY ATMOSPHERIC PREDICTIVE SKILL; LESS SENSITIVE TO ERRORS IN INITIAL STATE; MORE SENSITIVE TO ERRORS IN FORCING
2. SLOW (WEEKS TO MONTHS) AND INDIRECT	MESOSCALE EDDIES, MEANDERING CURRENTS, FRONTAL LOCATIONS, FEATURES RELATED TO FLOW INSTABILITIES ON THE MESOSCALE	FORECAST MAY HAVE RANGE OF MONTH OR MORE; MORE SENSITIVE TO INITIAL STATE; LESS SENSITIVE TO ERRORS IN FORCING; STATISTICS MAY BE PREDICTED VIA SIMULATION; REQUIRES OPERATIONAL OCEANOGRAPHIC DATA; ALTIMETER DATA PROMISING
3. SLOW (WEEKS TO YEARS) AND DIRECT	EL NINO; MUCH OF THE TROPICAL OCEAN CIRCULATION; GYRES; PATTERNS ASSOCIATED WITH GEOMETRIC CONSTRAINTS (MEDITERRANEAN CIRCULATION)	LONG RANGE FORECAST POSSIBLE; SENSITIVE ONLY TO ERRORS IN FORCING ON LONG TIME SCALE; "NOWCASTING" AND FORECASTING FEASIBLE USING OCEAN MODELS WITH SPARSE OCEAN DATA

* Adapted from Hurlburt, 1984.

for the North Atlantic. Because the available operational data, particularly below the surface, is so sparse (even for the "well-observed" Atlantic), the demands on our prediction models and assimilation schemes are far greater than for the atmospheric equivalent. Although ocean simulation is now a widely recognized tool for understanding nonlinear, time-dependent ocean dynamics, proceeding to models for ocean *prediction* is a major qualitative leap. We must still determine if our best simulation models are also our best ocean prediction models.

Simulation studies and at least rudimentary prediction systems have been developed for each class of forcing. In Class I, the global Thermodynamic Oceanographic Prediction System (TOPS) mixed-layer forecast model was developed at the Naval Ocean Research and Development Activity (NORDA) in the early 1980s, drawing on university and in-house research, and has been operational at Fleet Numerical Oceanography Center (FNOC) for several years (Clancy and Pollack, 1983; Rosmond, 1992, this issue). In Class III, models are now being used for El Nino prediction with some apparent forecast skill (i.e., forecast capability) (Barnett *et al.*, 1988). A Class II capability is now emerging, as we show below.

Limited-Area Gulf Stream Models

For Class II problems, the first limited-area Gulf Stream prediction models are now operational and have shown some forecast skill superior to persistence (no change) at 1 and 2 weeks (Fox *et al.*, 1991 and 1992, this issue; Robinson, 1992, this issue). Figure 1 shows a simulated Gulf Stream in a limited-area $\frac{1}{12}$° horizontal-resolution two-layer model. The model design is basically as described by Thompson and Schmitz (1989). Elements of this simulation are specified constant inflow transport, a radiation condition on the entire eastern boundary, bottom topography, and mean wind forcing. The model is run to statistical equilibrium Thompson and Schmitz (1989) demonstrate that a realistic mean Gulf Stream path can be obtained in this model only if the Deep Western Boundary Current is included as an additional source of potential vorticity. Without it, the Gulf Stream "overshoots," hugging the coast and separating near 40° N. This problem of overshoot has been seen in a number of eddy-resolving ocean models and is presently the subject of substantial research (Cessi, 1990; Ezer and Mellor, 1992). Although there are numerous alternative explanations (buoyancy and momentum forcing, model resolution, model formulation, to-

We must still determine if our best simulation models are also our best ocean prediction models.

pographic and coastal processes) hypothesized as important in the separation process, much is still unexplained. Thermocline ventilation to the north of the Gulf Stream is likely to be a critical element of the dynamics (Huang, 1991).

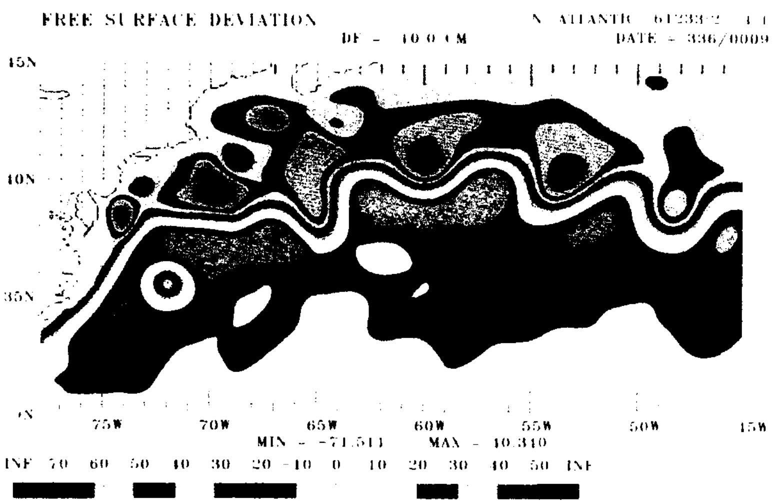


Fig. 1: Sea-surface height (cm) snapshot at year 10 from the Naval Research Laboratory Limited-Area Model of the Gulf Stream. The model has two layers, with bottom topography, constant inflow (50 SV) and includes a Deep Western Boundary Current (20 Sv). (1Sv = 50 × 10⁶ m³ sec⁻¹).

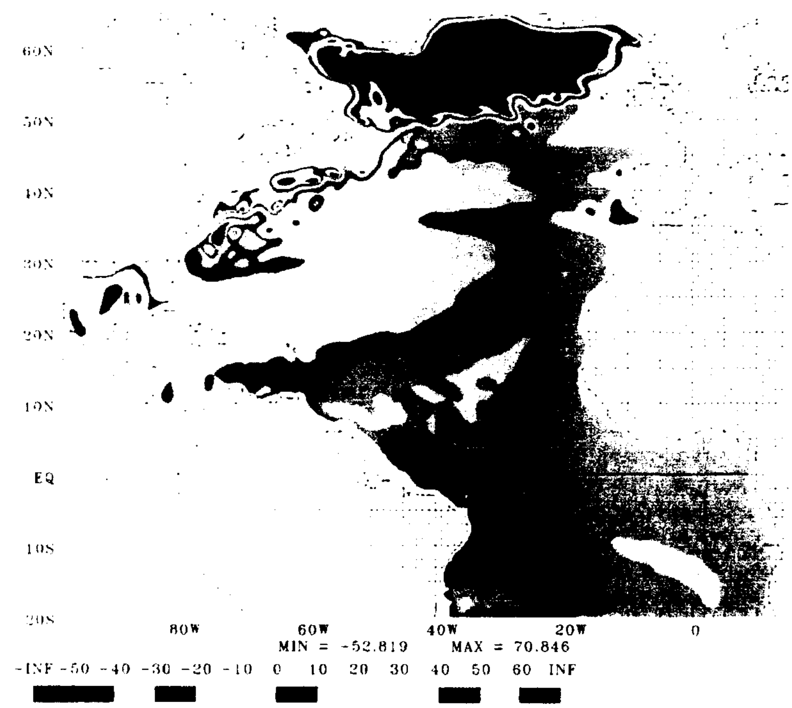


Fig. 2: Sea-surface height (cm) snapshot of the basin-scale North Atlantic model at $\frac{1}{8}$° horizontal resolution in year 17, forced by Hellerman-Rosenstein (1983) monthly mean wind climatology. This is one of the first eddy-resolving basin-scale models with realistic geometry run on the new Navy Cray YMP at the Naval Oceanographic Office.

Our work has shown that a realistic model climatology, including the mean path of the Gulf Stream and recirculation, is an essential component of the forecast system. Using model statistics to relate surface fields to subsurface fields, we obtain a dynamically consistent initial state using surface information from infrared data, altimeter data, and "feature models" (Hurlburt *et al.*, 1990; Fox *et al.*, 1991). This initial state is critical for forecasting the Gulf Stream evolution on time scales of days to weeks. Large initial imbalances, particularly at depth, can excite internal and external gravity waves as well as topographic Rossby waves. These wave motions can swamp the true field and destroy a forecast over the time scale of interest.

Basin-Scale Models

Although the limited-area modelling work is shown to be feasible and skillful in the Gulf Stream, it is clear that for longer time scales, wider coverage, and with a variety of assimilation schemes expansion of the model to basin and global scales is necessary. In the past decade, idealized basin-scale eddy-resolving models have become sufficiently realistic and the data sufficiently extensive so that modelers and observationalists have begun to compare their respective results, particularly in the Gulf Stream System (Schmitz and Holland, 1986). Limits on computational resources and data sources require simplification and intelligent model design to maintain a feasible, cost-effective eddy-resolving capability. Recently, physically comprehensive basin-scale models of the North Atlantic nearly able to resolve eddies have been developed for the World Ocean Circulation Experiment (WOCE) in the Community Modeling Experiment (CME) for multiyear simulations in ocean climate studies (Bryan, 1990). Several other Atlantic basin-scale or global models also have been developed but are not yet truly eddy-resolving (Semtner and Chervin, 1988; Bleck and Smith, 1990).

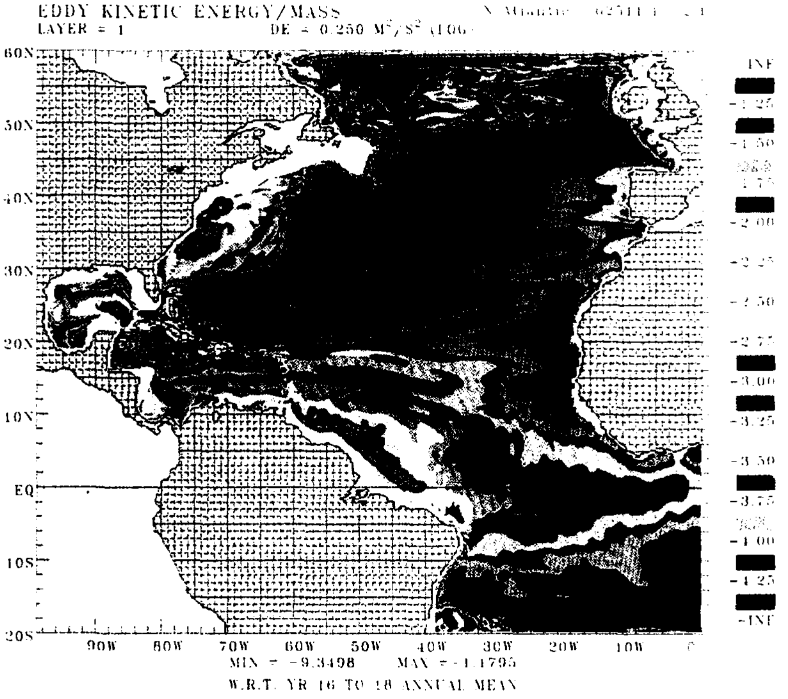
Figure 2 shows a snapshot of sea-surface height from the Navy's basin-scale eddy-resolving model of the North Atlantic. This two-layer primitive-equation model is a descendent of the semi-implicit layered formulation of Hurlburt and Thompson (1980), where the model equations have been vertically integrated through each layer. Laplacian friction and a quadratic bottom stress are included. This version has closed boundaries and bottom topography and was driven by the monthly wind stress climatology of Hellerman and Rosenstein (1983) to statistical equilibrium at $\frac{1}{4}$° horizontal resolution and then interpolated to $\frac{1}{8}$° and the integrations continued. Computations were performed on the Navy's new Primary Ocean Prediction System (POPS-1) at the Naval Oceanographic Office, Stennis Space Center, Mississippi. The heart of POPS is a 128 million-

word, 8 processor CRAY YMP. The first results on the new machine were obtained in late 1990, and currently both local and remote laboratory and university users are supported. Note that in Figure 2 both Gulf Stream meanders and cold and warm core rings are simulated by the model.

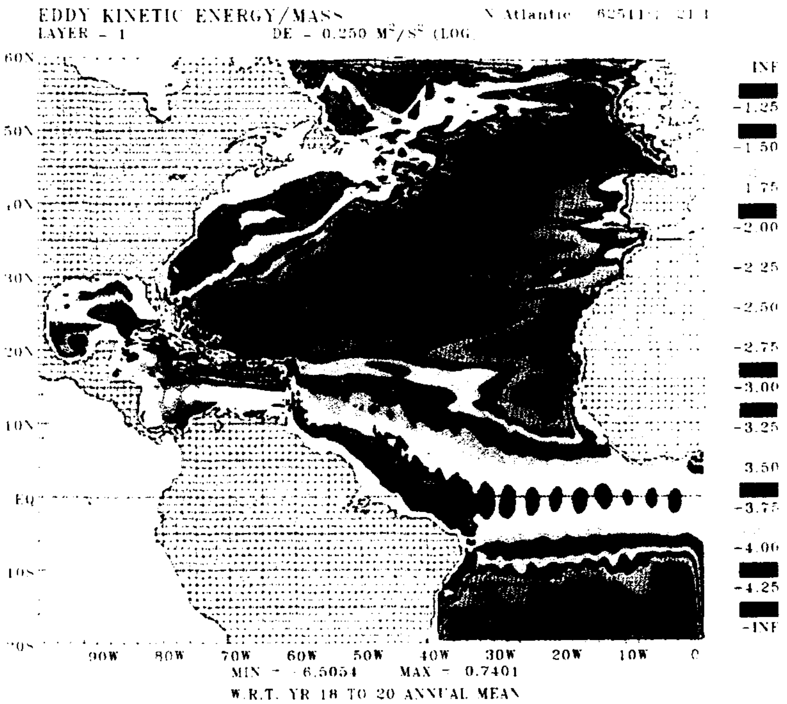
Although Figure 2 shows results from a closed basin, it is clear that a thermally driven, cross-equatorial flow from the South Atlantic is an important component of the Gulf Stream transport. Recently the Atlantic "conveyor belt," which includes the thermohaline contribution to the flow, has received particular attention in relation to ocean climate (Gordon, 1986). Schmitz and Richardson (1991) have estimated that nearly one-half of the transport in the Florida Current has its origin in the South Atlantic. Thus, the thermohaline component of the Gulf Stream System must be taken into account, even in relatively short-time-scale mesoscale prediction. Figure 3 shows results from two identical 1.5-layer reduced-gravity model experiments at $\frac{1}{4}°$ horizontal resolution driven to statistical equilibrium by the monthly mean winds of Hellerman and Rosenstein (1983). One experiment is with a closed basin. The other experiment is with a 15-Sv inflow-outflow included, with the source being a 20°-wide prescribed inflow at 20°S and the sink occurring at 60°N, also through a 20°-wide open boundary. Note that the eddy kinetic energy maximum in the Gulf Stream region is nearly a factor of three larger in the experiment with South Atlantic inflow. Also note the highly energized equatorial wave guide in the experiment with inflow. The dynamics of cross-equatorial flows and related instability processes is an exciting topic of current basic research (Kawase *et al.*, 1990).

Model/Data Comparisons

Validating basin-scale models for mesoscale prediction is itself an important research activity. Finding appropriate measures for comparison is not always straightforward. The deep eddy-kinetic-energy field is particularly illuminating for model/data comparisons (Thompson and Schmitz, 1989), as are comparisons of model sea-surface-height variability with altimetry (Hallock *et al.*, 1989). Another interesting data set for validation is the long-term transport measurements of the Florida Current. A 10-year time series is now available from the National Oceanic and Atmospheric Administration (NOAA), Subtropical Atlantic Climate Studies (STACS) program (Schott *et al.*, 1988), using submarine electromagnetic cable estimates calibrated by direct velocity observations between Jupiter, Florida and Settlement Point, Grand Bahama Island near 27°N. The daily STACS data have been low-pass filtered (30–40 day cutoff) and are plotted in Fig-

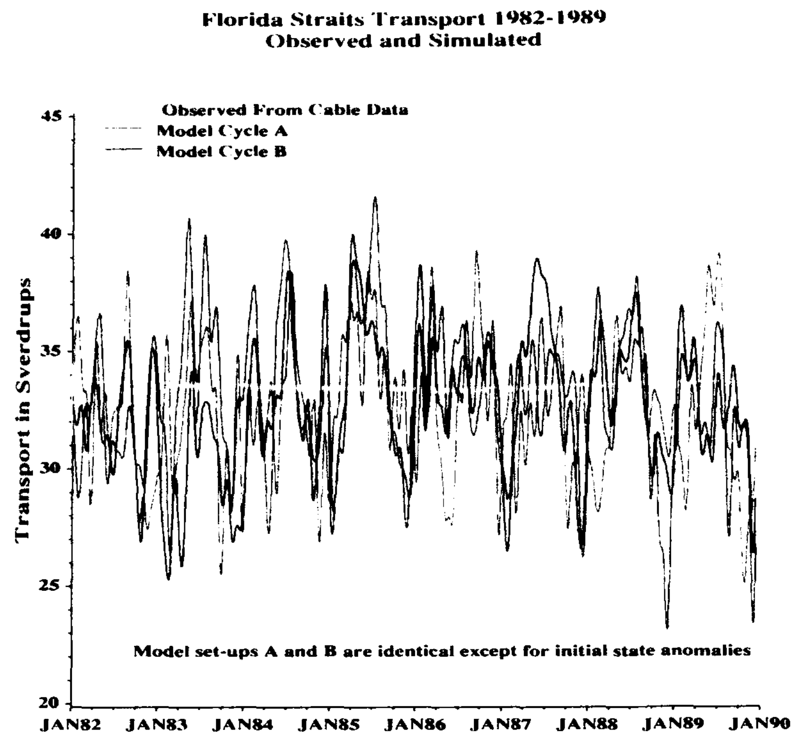


(A)

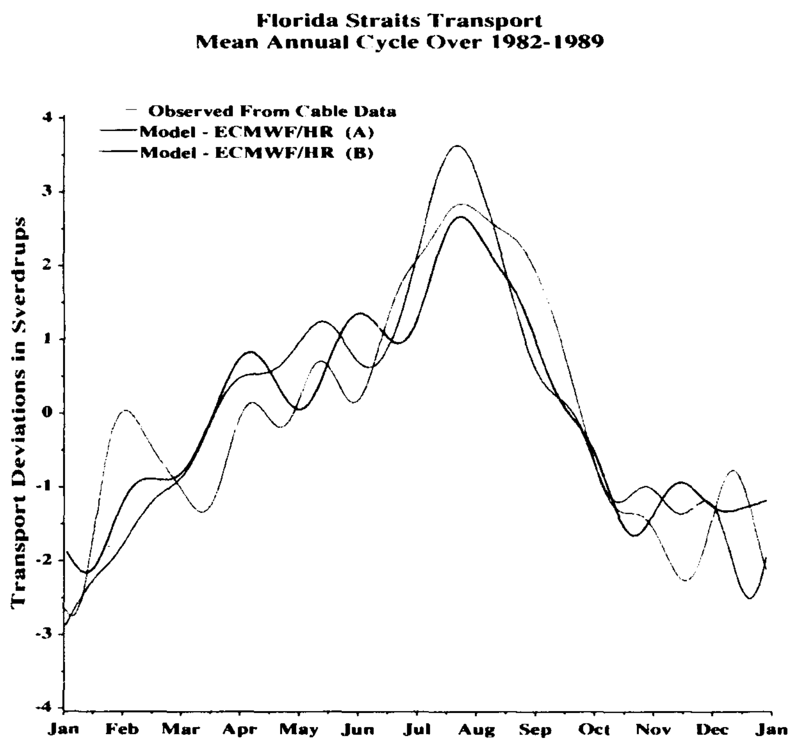


(B)

*Fig. 3: Contours for the log of eddy kinetic energy from a 1.5-layer reduced-gravity model driven by Hellerman-Rosenstein (1983) monthly mean winds to statistical equilibrium: (**A**) in a closed basin and (**B**) with a 15-Sv South Atlantic inflow and a high-latitude outflow. Maximum eddy kinetic energy is 0.07 $m^2\ s^{-2}$ and 0.19 $m^2\ s^{-2}$ in **A** and **B**, respectively.*



(A)



(B)

*Fig. 4: (**A**) Calibrated cable-estimated volume transport of the Florida Current from the Subtropical Atlantic Climate Studies Program (STACS) at 27°N (courtesy Jimmy Larsen, NOAA, Pacific Marine Environmental Laboratory, Seattle) versus model-determined transport for two different 8-year cycles of the same European Centre for Medium-Range Weather Forecasts wind forcing. Observations and model data were low-pass filtered (30–40 day cutoff) and plotted daily. (**B**) The annual cycle of transport from the STACS data and from the two model cycles.*

ure 4A. Note the mean transport is near 32.5 Sv and the maximum transport occurs on the summer.

Earlier models have shown the summertime transport maximum observed in the STACS Program. For example, Anderson and Corry (1985) used a non-eddy-resolving two-layer basin-scale model driven by monthly mean wind anomalies from Hellerman and Rosenstein (1983). Rhodes and Heburn (1986) used a global, coarse-grid reduced-gravity model driven by FNOC operational wind fields. However, both models failed to account for the large amplitude of the annual cycle of transport and the magnitude of the mean transport.

In Figure 4A, we also have plotted transports from a three-layer, finite-depth model driven to equilibrium by the monthly mean climatological winds (Hellerman and Rosenstein, 1983) for 70 years and then run for more than two 8-year cycles of winds having the annual mean from Hellerman and Rosenstein (1983), but anomalies about the mean from the European Centre for Medium-Range Weather Forecasts (ECMWF) operational winds. This is one of the few long time series from an operational center that has a reasonably consistent wind field from year to year. Constant South Atlantic inflow was specified from estimates of Schmitz and Richardson (1991) and high-latitude water-mass formation was parameterized via entrainment/detrainment and a source-sink flow. We have plotted two wind cycles to show the interannual differences in transport from the model due to differences in initial state and nonlinear processes, including influences of Loop Current eddy shedding in the Gulf of Mexico. Two important results from this experiment are clear: 1) The mean transport of the model current is nearly identical to that observed. The South Atlantic inflow comprises about 13 Sv of this total. 2) The amplitude of the fluctuations in transport are comparable to those observed, including the summertime maximum and the rapid decrease in transport in the fall. The annual cycle, as shown in Figure 4B, also is reproduced well by the model. These results give us some confidence in both the model and the forcing functions.

Finally, although we are rapidly pushing toward an eddy-resolving basin-scale prediction capability in NOMP, we should note that a global, non-eddy-resolving model driven by FNOC Navy Operational Global Atmospheric Prediction System (NOGAPS) winds is running on a daily basis under an operational evaluation program. Figure 5 is a snapshot of the sea-surface height for 25 January 1992 from this $\frac{1}{2}$°, reduced-gravity model. It is clearly only a preliminary version of the model we hope will eventually be running on a routine basis with data-assimilation and eddy-resolving capability. However, as discussed in the article by Hurlburt *et al.*, (1992, this issue), we are rapidly approaching the day when this capability will be realized.

Acknowledgements

This work was supported by the Navy Ocean Modeling and Prediction Program (Bob Peloquin, Program Manager), under the Global Ocean Prediction System project (Program elements 62435N and 63207N), the Naval Research Laboratory's Global Eddy-Resolving Ocean Model basic research program, and the Office of Naval Research Accelerated Research Initiative entitled "Ocean Dynamics from GEOSAT." Discussions with Harley Hurlburt and George Maul have been especially useful.

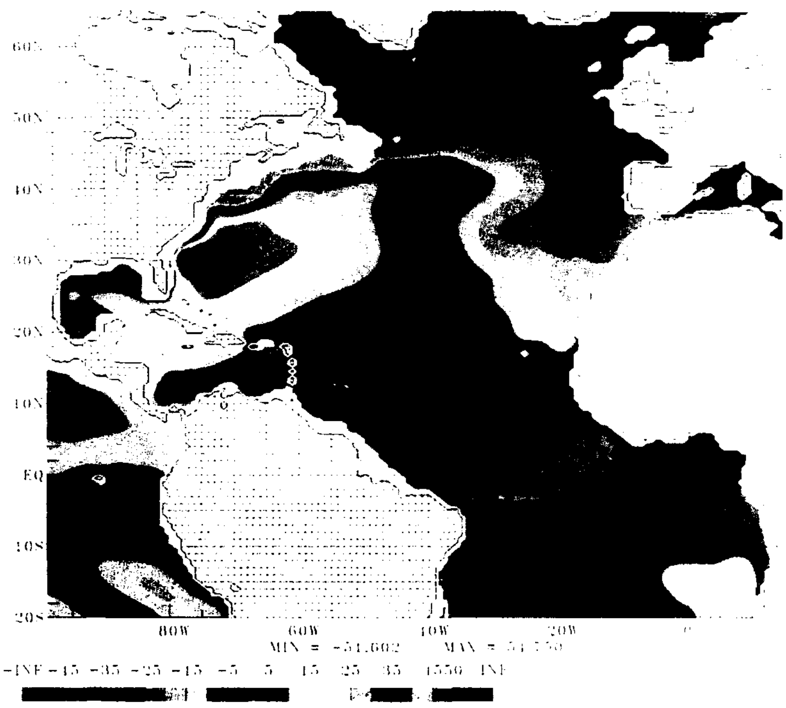


Fig. 5: Sea-surface height (cm) from a global non-eddy-resolving reduced-gravity ocean model driven by operational Fleet Numerical Oceanography Center winds. Map is for 25 January 1992.

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SHIPBOARD PREDICTION WITH A REGIONAL FORECAST MODEL

By Allan R. Robinson

The new opportunities for ocean scientific studies and efficient marine operations involve the estimation of realistic physical fields.

RECENT advances in the knowledge of physical structures in the ocean and progress in the understanding of related physical processes present new opportunities for realistic ocean scientific studies and efficient marine operations. Over the past two decades, typical synoptic structures of energetic mesoscale meanders and eddies have been determined. Some regions of the world ocean, such as the Gulf Stream system are relatively well observed and studied, whereas others, such as the North Atlantic Current system, still require descriptive research. However, modern methods and strategies can yield rapid results when previously unexplored regions are investigated. New instruments, platforms, sampling schemes, and particularly the coverage afforded by satellite-borne sensors are all contributing to the new knowledge of the physical fields. Dynamical studies, modeling, and simulations provide understanding and feedback. Numerical ocean modeling, which is essential for the representation of realistic fields, is developing very rapidly. Critical support is provided by advances in computer software and hardware, including both supercomputers and workstations.

The new opportunities for ocean scientific studies and efficient marine operations involve the estimation of realistic physical fields. Such field estimations include nowcasts, forecasts, and simulations, which are constructed via the assimilation of data into dynamical models. Dynamical adjustment and dynamical interpolation most efficiently exploit available data, and the melded observational and model-based estimates resulting from assimilation are essentially necessary in oceanography. This is because many mesoscale features occur in large-scale domains of interest, making extensive direct mapping (from observations alone) prohibitively demanding of resources. The realistic physical-field estimates (velocity, pressure, temperature, and salinity) may be directly utilized or may serve as the basis of dynamical studies via the investigation of vorticity balances and energy exchanges. Also, very importantly, these fields provide, for the first time on a very substantial and extensive basis, the possibility of interdisciplinary ocean studies and applications. They represent the four-dimensional (space-time) structures that advect, entrap, and mix dissolved and small-particulate matter. These processes control critical aspects of the dynamics of biogeochemical cycles and ecosystems. They are essential elements of any management model relating to pollution control and resource exploitation and conservation. Such physical nowcast and forecast fields provide, for the first time on a substantially realistic basis, the opportunity for three-dimensional range-dependent acoustic propagations and forecasts. We will focus on the latter application in this review.

A dynamical forecast is a real-time estimate of the future state of the ocean obtained by running a dynamical model forward in time. A hindcast is a forecast made later than real time. A nowcast is an estimate of the present state of the ocean based on melding observations and dynamics. New observations may be melded with a previous forecast or may be used to initialize a short dynamical model run for adjustment and interpolation purposes. Real-time nowcasts and forecasts are important for operations at sea, including those of a scientific nature. Mesoscale phenomena are variable and intermittent in space and time. The location and prediction of events and instrument sites can increase significantly the efficiency of resource use. Predictions, accurate enough to be useful and efficient enough to be feasible, must now be performed on a regional basis. Mesoscale space scales range from tens to hundreds of kilometers and time scales from days to months. Data requirements cannot now be met on a global or basinwide scale. Even if this were not the case, the intellectual, technical, and methodological basis for phenomenological interpretation and quality control on such large scales is not yet available. In any case, operational domains of interest are usually limited to domains of a few hundreds or thousands of kilometers in extent.

In many instances, it is desirable to perform the regional forecast at sea aboard an operating

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vessel. The vessel itself can gather the requisite initialization and updating data, *in situ* subsurface data and/or satellite data. The forecaster may be located aboard the vessel. No communication system is required for a stand-alone operation. The advent of powerful small computers, which are easily carried on and off ships, makes shipboard predictions feasible and convenient today.

The remainder of this article describes a flexible and portable regional forecast system, its shipboard use in real time, and its coupling to an acoustic propagation system. A real-time at-sea exercise in the Northeast Atlantic during the summer of 1987, which involved the shipboard use of Geodetic Earth Orbiting Satellite (GEOSAT) altimetric data, is presented. This exercise provides the basis for a proof-of-concept feasibility demonstration for the fully coupled environmental/acoustical system, with which we conclude.

The Coupled Environmental/Acoustical System

To carry out acoustic propagation forecasts in realistic range-dependent environments requires the coupling of a physical-field environmental-forecast system to an acoustic-propagation system. The term system is used to emphasize that the forecasts and their associated sensitivities and error characteristics depend upon a number of factors. For each system these include physical and mathematical modeling assumptions, qualitative and quantitative aspects of the data base, and computational algorithms and parameters. Additionally, the scheme for inputting sound speed distributions to the acoustic system from the environmental system's output of temperature, salinity, and pressure introduces dependencies and sensitivities. This section discusses some of the issues and factors affecting the accuracy and sensitivity of the coupled system and its validation.

The environmental system's dynamical model component (O'Brien, 1986) has explicit physics governing the scales of motion resolved by the horizontal and vertical numerical grids. In other words, the continuous dynamical equations of motion are discretized by an algorithm. But there are also physical processes on scales too small to be resolved by the numerical grids. The subgridscale physics governing the unresolved scales is given a parametric representation (Holloway, 1989). The fundamental (Navier-Stokes) fluid dynamical equations of motion are never solved directly for the scales of motion relevant here. Geometrical and dynamical approximations are employed with the constraints of the earth's rotation and of stable stratification introduced. The primitive equation (PE) approximation, which retains general dynamical balances in the horizontal but which is approximately hydrostatic in the vertical, is appropriate for mesoscale motions. Further simplifications are often desirable to gain efficiency or to control aspects of the physics. Most mesoscale dynamical phenomena are almost geostrophic, and the quasigeostrophic (QG) approximation provides an accurate time evolution for the flow field. Exceptions are some interactions with steep topography and aspects of intense meandering of strong jets. The representation of subgridscale physics is difficult and complex. Various nonlinear processes and interactions and turbulent effects may be relevant. Distinction needs to be drawn between horizontal processes (or alternatively, processes along constant-density surfaces) and vertical processes (or alternatively, processes across density surfaces). Practice ranges from the use of simple, constant eddy diffusivities to the use of sophisticated representations of turbulent effects and closure hypotheses. Potential acoustic effects, related to the subgridscale assumptions of the dynamical model influencing the field estimates, are not yet known.

. . . forecasts and their associated sensitivities and error characteristics depend upon a number of factors.

In addition to the dynamical model, the environmental system has a statistical model component and a data assimilation scheme. The statistical model must serve to interpolate data and to put the data onto a regular grid. This is usually done by an objective analysis or optimal interpolation scheme, which minimizes some expected error norm (Bretherton *et al.*, 1976; Clancy *et al.*, 1990). Extrapolation, of special importance for the downward extension of satellite observations, may be accomplished on dynamical modes or empirical orthogonal functions (Preisendorfer, 1988). Additionally, feature models which are average synoptic structures (with a few degrees of freedom) are employed to minimize data requirements and to extend satellite observations before assimilation into the dynamical model. Data assimilation has recently entered oceanography and considerable research has been started to determine the advantages and sensitivities of various schemes in various situations of oceanographic interest (Anderson and Willebrand, 1989; Haidvogel and Robinson, 1989). Schemes range from simple optimal interpolation to the more complex variationally based inverse and adjoint methods. Computational efficiency considerations are paramount. The data bases required include the bottom topography, climatology, surface fluxes, and synoptic data for initialization and updating. An observational network with a mix of remotely sensed and *in situ* data types is usually the most efficient.

The dynamical model of the acoustical system also is usually an approximation to the fundamental Helmhotz equation. Assumptions depend on the frequency range and the specific physics and geometry considered. Ray theory, the parabolic-equation approximation for the far field, and normal modes are frequently used (Potter and Warn-Varnas, 1991). In addition to the four-dimensional sound speed distribution, environ-

mental and boundary conditions associated with the sea surface and bottom (and the underlying sediments) can produce a number of phenomena, which may or may not be important and may or may not be explicitly included in the propagation calculation. In considering the coupling, it is important that the environmental model evolve satisfactorily those structural features which affect the acoustics, even though they may not be important for the dynamical evolution of the main mesoscale fronts and eddies. Also, the acoustic model requires a vertical and horizontal grid of sound-speed input of much higher resolution than is necessary or efficient for the running of the ocean dynamical model. Thus interpolation is required and research in relevant methodology is currently underway.

The Forecast System

Our physical oceanography group has developed a versatile open-ocean forecasting system. The system is flexible and portable both scientifically and logistically. Since 1980, it has been exercised and validated at 11 sites in the world ocean as shown on the map of Figure 1. All but the original POLYMODE* site involved real-time forecasts, and at six sites the real-time forecasts were carried out aboard ships. Synoptic data input has included temperature and salinity profiles, current measurements, and both sea-surface temperature and height sensed from satellites.

. . . a versatile open-ocean forecasting system . . . has been exercised and validated at 11 sites in the world ocean.

The original dynamical model component is an open-ocean quasigeostrophic model that was developed to study the dynamical processes inherent in local intensive data sets. The approach involved real data initializations of a block of open ocean and thus encompassed the forecast problem. A review of this work, including the system's multivariate objective analysis scheme and the associated energy and vorticity analysis scheme, is presented by Robinson and Walstad (1987). The present forecast system is based on a dynamical model hierarchy. There is a set of models with dynamics and geometry appropriate to various oceanic regions. The QG model has been generalized to domains that may be partially open and partially closed by arbitrary coastlines and may contain islands (Özsoy *et al.*, 1991). A three-dimensional surface-boundary-layer (SBL) model has been coupled to the full water-column eddy-resolving model (Walstad, 1987) to represent the details of upper-ocean physics. A primitive-equation open-ocean model for the water column has been developed (Spall and Robinson, 1989) starting from the basic Geophysical Fluid Dynamics Laboratory primitive equation model (Bryan and Cox, 1967). The horizontal subgridscale physics in both the PE and QG models is a smoothing operation via an arbitrary order Shapiro filter (Robinson and Walstad, 1987). This prevents the build-up of energy in small scales of the numerical grid, which would otherwise occur due to the enstrophy cascade of geostrophic turbulence. Present data assimilation schemes include optimal interpolation and for the QG model, an efficient adjoint (Moore, 1991).

The first real-time forecast was carried out in 1983 in the context of the Ocean Prediction Through Observation, Modeling and Analysis (OPTOMA) program at the Naval Postgraduate School, by radio communication with the R/V Acania, which was gathering data in the California Current (Robinson *et al.*, 1986). In 1984, the dynamical model was first taken to sea on a microcomputer, and used in the Nares Plain region of the Northwest Atlantic. Dr. L.J. Walstad and Mr. W.G. Leslie took it to forecast for real-time experimental guidance (Robinson, 1986). These and related studies led to the development of the modular concept of dynamical model initialization with *in situ* data being acquired in real time. A full mapping grid is not necessary. Dynamical interpolation can be successfully carried out into the interior from data taken on the boundaries of a square module. Each module is somewhat less on a side than the eddy-decorrelation length scale. A large region can be efficiently built up from a number of adjoining modules with reinitializations and updates. Once the full domain of interest has been initialized, only the boundaries need updating to maintain most open-ocean regional nowcasts and forecasts for a considerable length of time. When satellite or aircraft data are also available, other initialization and updating strategies are more efficient, and even less *in situ* data is required. Although direct current measurements are desirable, they are not always essential because hydrography or altimetry plus model dynamics can together provide the unmeasured barotropic mode (Robinson *et al.*, 1986; DeMey and Menard, 1989).

The Gulf Stream meander and ring region has been the location of considerable research on dynamics and prediction during the past several years. Starting in 1986, for a period of over 2 years, the group at Harvard carried out with Navy support 1-week-duration day-by-day forecasts (Gulfcasts) of the Gulf Stream frontal and ring locations and interactions (Robinson *et al.*, 1989). Initialization and updating nowcasts melded dynamical model forecasts with new observations of frontal locations obtained from satellite infrared sea-surface temperature and GEOSAT altimetric sea-surface heights. Also, there was nominally, once a week, a dedicated P3 AXBT flight, i.e., a Navy patrol aircraft dropped ~35 temperature versus depth probes in specially identified locations. Approximately 75% of the ring-birth and reabsorp-

* A program name derived from the Russian word polygon that means moored array and the US-UK acronym for Mid-Ocean Dynamics Experiment.

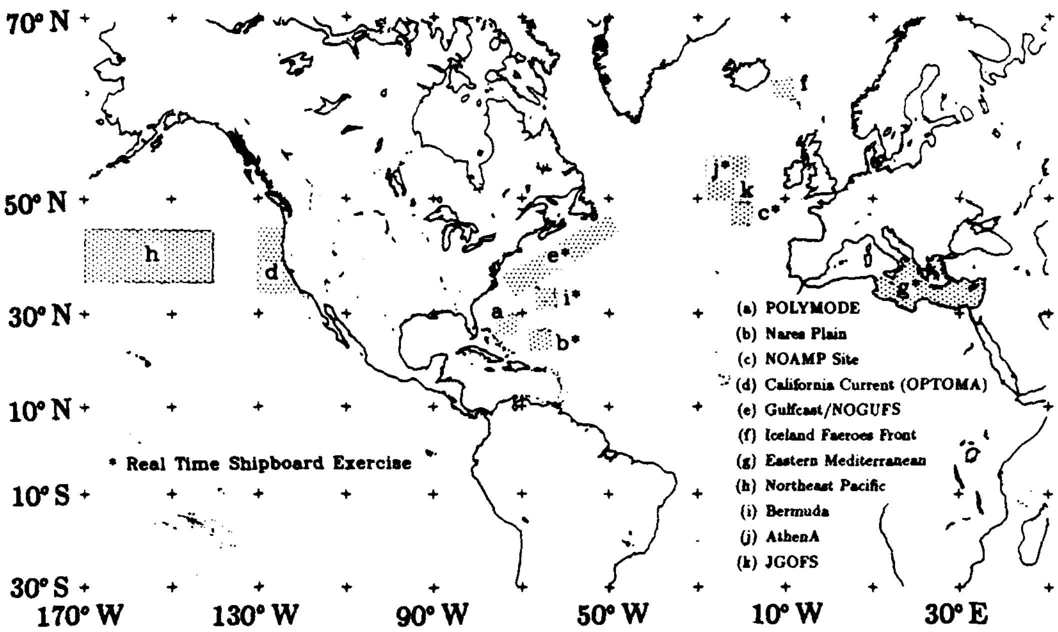

Fig. 1: Locations of operation of the Harvard forecast system. POLYMODE: POLYgon—Mid-Ocean Dynamics Experiment. NOAMP: NOrth Atlantic Monitoring Program. OPTOMA: Ocean Prediction Through Observation, Modeling and Analysis. NOGUFS: Naval Operational GUlf stream Forecast System. AthenA: Acquisition de données de Topographie de surface et d'Hydrologie dans l'Est Nord Atlantique. JGOFS: Joint Global Ocean Flux Study.

tion events were forecast correctly, and *a posteriori* verification of the Stream frontal location offsets with GEOSAT data (Glenn *et al.*, 1991) yielded a standard deviation of ~30 km, the noise level of the system. In December 1989, the system was transferred for operations to the Naval Oceanographic Office [with the name Naval Operational GUlf stream Forecast System (NOGUFS)] and was cited by Rear Admiral J. Koehr as "the Navy's first dynamic oceanographic forecast model." The opportunity provided for realistic acoustic propagation studies by the Gulfcast fields resulted in their utilization by acousticians at a number of institutions including the Naval Oceanographic and Atmospheric Research Laboratory, the Naval Underwater Systems Center (NUSC, New London and Newport), the Woods Hole Oceanographic Institution, and the Naval Postgraduate School. In particular, an ongoing collaboration has developed between the Harvard group and Dr. D. Lee of NUSC (New London) and Professor W. Siegmann of Rensselaer Polytechnic Institute in coupling their parabolic equation propagation model, implemented numerically as the Implicit Finite Difference (IFD) model (Lee *et al.*, 1981), to Harvard dynamical model outputs. Sensitivity studies (Siegmann *et al.*, 1990) and fully three-dimensional results (Lee *et al.*, 1989) have been obtained.

A two-dimensional version of the IFD model now resides at Harvard. It has been coupled to the output of the full dynamical model hierarchy, PE, QG, and SBL and completes the present version of the Harvard environmental/acoustical forecast system. Two dimensions are accurate for most propagation situations, with exceptions including regions of strong azimuthal topographic variation (Siegmann *et al.*, 1990) A realistic sediment layer is included and important. Carman (1991) has used this system to study combined oceanographic and topographic effects on acoustic propagation (in regions e, f, and j of Fig. 1).

A Real-Time Exercise and Proof-of-Concept for the System

Site j (Fig. 1), in the Northeast Atlantic, was the location of a real-time experiment during July and August 1987, carried out on board the French Naval vessel *B.O.D'Entrecasteaux*. The objectives of the experiment, called Acquisition de données de Topographie de surface et d'Hydrologie dans l'Est Nord Atlantique (AthenA), were related to the methodology of real-time shipboard prediction using a dynamical forecast system and a combination of *in situ* and remotely sensed data. Harvard scientists participated with the quasigeostrophic model run on one of the group's SUN-3 workstations. The ship received GEOSAT altimetric data in near real time, transferred via Harvard from the Johns Hopkins University Applied Physics Laboratory, which was used for GEOSAT and model validation. The ship also received sat-

. . . "the Navy's first dynamic oceanographic forecast model" . . . provided for realistic acoustic propagation studies . . .

. . . forecast height field compared with an independent estimate from a GEOSAT pass . . . The agreement is again excellent . . .

ellite infrared imagery. The experimental domain was an open-square block of water 210 km on a side with a fairly flat bottom, which contained energetic mesoscale eddies associated with the North Atlantic Current and Drift. Two synoptic realizations of the hydrographic fields were obtained with Conductivity-Temperature-Depth sensors (CTDs) and expendable bathythermographs (XBTs) just over 2 weeks apart. Drifting buoys and current meters provided absolute flow measurements. More details can be found in Carman's (1991) thesis and a French report (Le-Squere, 1989).

Shipboard activities included real-time objective analyses and dynamical forecasts with six levels in the QG model. Figure 2A shows the sea-surface height field (in meters) associated with the shipboard nowcast of the first synoptic realization centered on 29 July. Hydrography plus drifter data have been assimilated into the dynamical model. The north-south oriented front is the border between two eddies of opposite sign. The ~0.25-m drop across the front corresponds to a southward flowing geostrophic current of 0.60 m/s maximum. The diagonal line on Figure 2A is the ground track of the GEOSAT satellite. Figure 2C compares two independent along-track estimates of the sea-surface height for 29 July. The first is obtained from the nowcast (fine line), and the second from the altimetric data derived by a method based on subtracting the individual track from the time mean of all the altimetric data along that track. The agreement in shape and amplitude is excellent; the individual track absolute mean altimetric height is not known over such a short segment (Porter *et al.*, 1989). The validation of the GEOSAT altimetric topography is within the noise level of the system. During the next 2 weeks the eddy system evolved with the western cyclone moving to the southeast and the front shifting orientation as shown on Figure 2B. The height field (Fig. 2B) has been forecast for 17.5 days from the nowcast (Fig. 2A) initialization. Only the boundary condition has been updated with new information from hydrography and floats. Figure 2D shows the along-track forecast height field compared with an independent estimate from a GEOSAT pass on 15 August. The agreement is again excellent, which can now be regarded as a GEOSAT validation of the forecast system. Unfortunately GEOSAT data return during the experiment was very poor in the region. However, Dombrowsky and De Mey (1992) have made detailed comparisons of Harvard QG model forecasts with updated boundary conditions and the AthenA *in situ* data and finds very good agreement throughout the experiment.

For this type of mid-ocean eddy field the QG model is adequately accurate. The types of small differences that occur between PE and QG dynamics have been studied for a Northwestern Atlantic site by Spall (1989). However for domains only a few hundred kilometers on a side, the open-ocean PE of the Harvard model set is almost as efficient computationally as the QG, and its shipboard use is optional.

Because the AthenA experiment involved real-time forecasting at sea with a mix of remotely sensed and *in situ* data, it was selected for a proof-of-concept feasibility demonstration of the full coupled environmental/acoustical forecast system. The hindcast was carried out using the coupled quasigeostrophic/surface-boundary-layer dynamical models and the two-dimensional IFD parabolic model. The QG used nine levels, and the SBL used eight additional levels. The QG water-column model was run for 10 days, which is a reasonable length of time for main thermocline evolution without the need for boundary updating. The SBL forecast for the upper ocean, which requires an atmospheric forecast for surface flux input, was limited to 3 days, and sound was propagated at 50 and 100 Hz for various source depths on the third day. The arrows on the 6-m-depth temperature field of Figure 3A and the 125-m-depth QG streamfunction field of Figure 3B indicate the location of the vertical sections for the propagation calculations. The date is August 3,

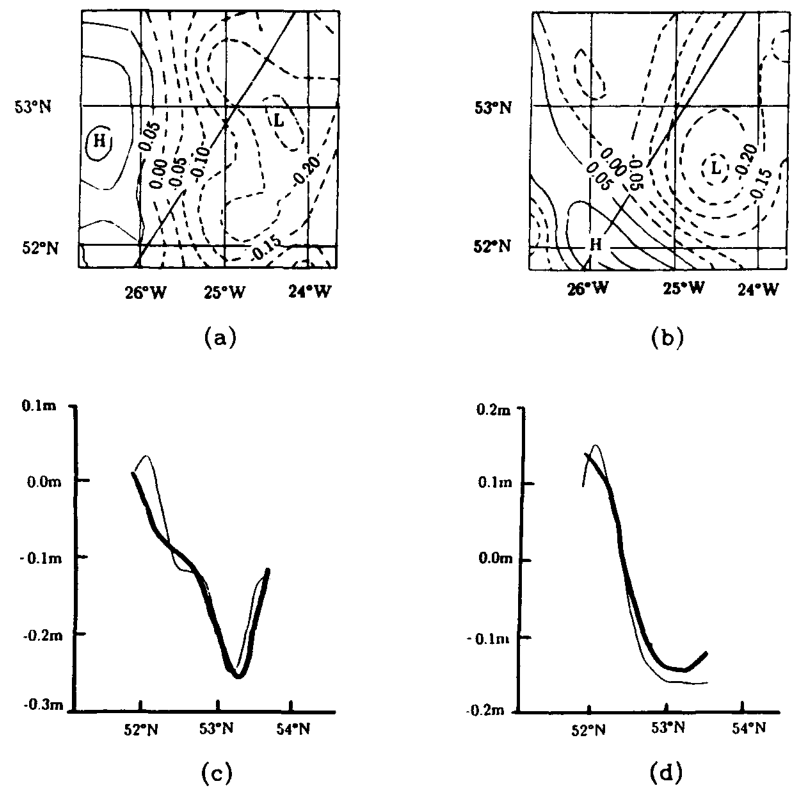

*Fig. 2: (**A**) Sea-surface height (meters) nowcast for 29 July 1987. (**B**) Forecast for 15 August 1987. GEOSAT track is the diagonal line. (**C**) Alongtrack comparisons of a nowcast (fine) and GEOSAT (bold) height estimates. (**D**) Alongtrack comparisons of **B** forecast (fine) and GEOSAT (bold) height estimates. Note the axis shift of 0.1 m between **C** and **D**.*

and the thermocline streamfunction field depicted in Figure 3B is proportional to geostrophic pressure or dynamic height (shown for July 31 in Fig. 2A). A difference of 20 nondimensional stream function units produces the geostrophic jet of ~60 m/s. Smaller-scale features are evident in the near-surface temperature. The sound speed section (Fig. 3C) indicates a sound channel axis, which rises to the east from ~900 to 500-m depth. Near-surface detailed structure is evident and the QG/SBL model treatment has increased near-surface sound speeds by ~5 m/s over a simple QG model forecast. Propagation in the sediment below the sea bottom included effects of a vertical sound speed gradient and an attenuation factor. An exemplary propagation-loss section is shown in Figure 3D for a 50-Hz source at 500-m depth. Detailed interpretation of the oceanographic effects on propagation are interesting but not the subject of this article. Carman (1991) finds eddy frontal effects of 45 dB. There is a near-surface duct that affects frequencies too low to be trapped. Changes as large as 25 dB occur relative to comparison calculations made without the SBL model coupled to resolve the near-surface structures. The bottom is nearly flat at just under 4500-m depth, except for a hill in the west. Note the propagation within the sediments, which influences the water-column propagation.

The efficiency of this portable and realistic forecast system can be measured by the clocktime required to produce the acoustic forecasts after the acquisition of nowcast data. The objective analysis took approximately one-half hour of SUN-3 workstation time, the 10-day QG forecast took 1 hour, and the 3-day SBL forecast one-half hour. The IFD propagations were run on an Iris, and 1 hour of clocktime yielded from 2 to 6 source cases dependent on frequency. Thus the system is very efficient with only 3–4 hours being required. Moreover the workstations used are no longer state-of-the-art. Currently available workstations could reduce the time required by a factor of 10 and allow improvements such as increased resolution and more sophisticated assimilation schemes.

Summary and Conclusions

The ability for the first time in ocean science history to forecast realistic physical fields makes realistic three- and four-dimensional range-dependent acoustical propagation now possible on a substantial basis. The concept of a coupled environmental/acoustical system has been introduced and factors affecting its accuracy discussed. A portable, flexible system that is feasible, accurate, and efficient for shipboard use has been described and its use illustrated in both the forecast and hindcast mode. Realistic real-time shipboard forecasts of practical interest can be achieved in only a few hours of clocktime.

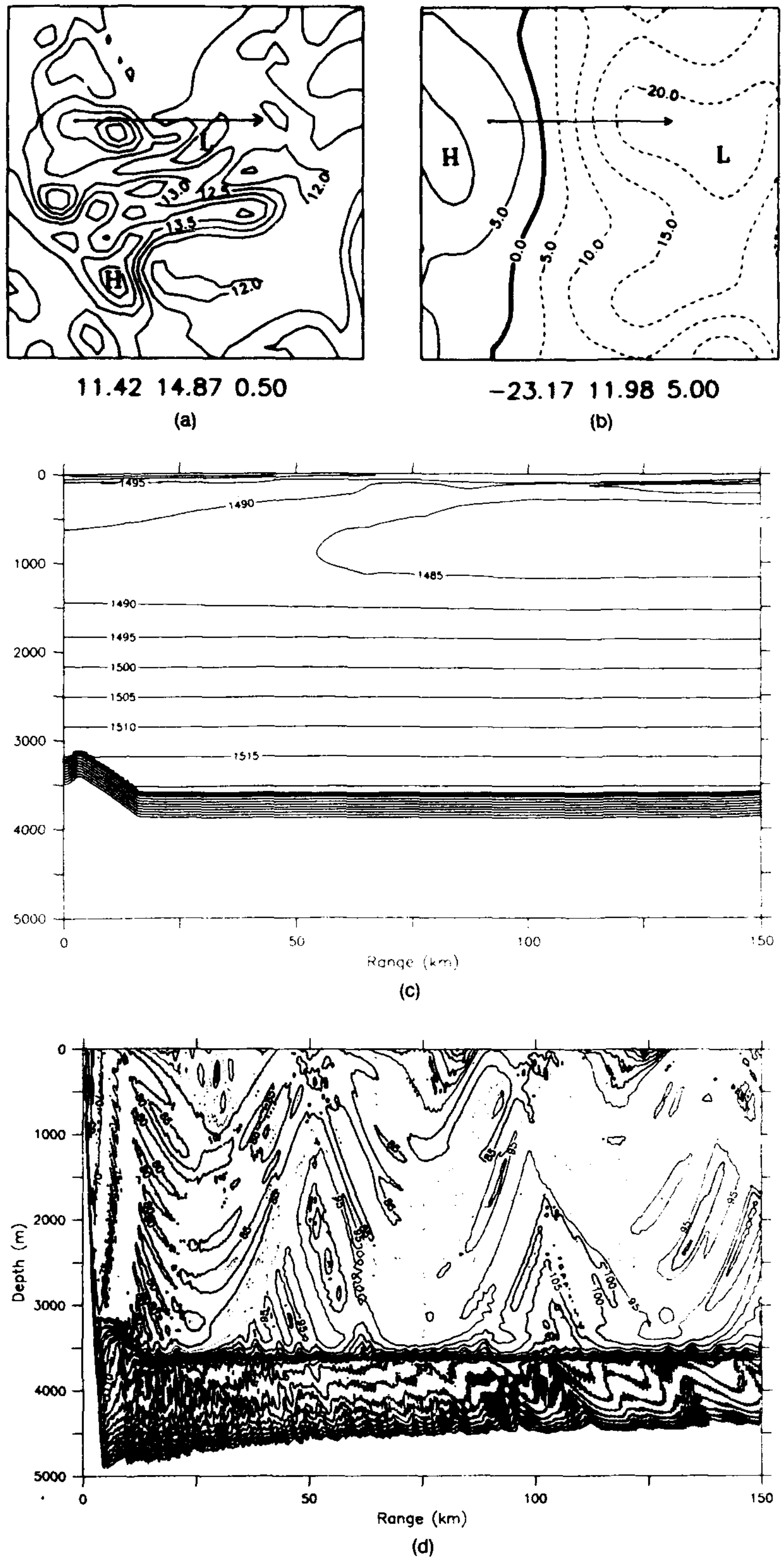

*Fig. 3: Three-day forecasts of (**A**) temperature at 6 m (0.5°C contours), (**B**) non-dimensional quasigeostrophic (QG) streamfunction at 125 m (arbitrary units; see text), (**C**) sound speed (m/s) and (**D**) propagation loss (decibels) for a 50-Hz source at 500 m. (Black 50–75 dB; red 80–85 dB; yellow 90–94 dB; green 95–99 dB; blue 100–170 dB). Minima, maxima, and contour intervals are labeled below **A** and **B**.*

Acknowledgements

The proof-of-concept hindcast was carried out at Harvard with the help of J.C. Carman, C.J. Lozano, A. Gangopadhyay, and D.J. McGillicuddy. L.J. Walstad, D.W. Denbo, and J.C. Carman performed the real-time nowcasts and forecasts during AthenA, and J. Calman, E.B. Dobson, and D. Porter provided the GEOSAT data. I thank A. Gangopadhyay, M.G. Cormier, W.G. Leslie, and C.J. Lozano for help in the preparation of the manuscript. ONR Support under grants N00014-90-J-1593 and N00014-90-J-1612 is gratefully acknowledged. The University Research Initiative contract N00014-86-K-0751 supported (in part) the real time exercises during AthenA.

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Characterizing Major Frontal Systems: A Nowcast/Forecast System for the Northwest Atlantic

By Daniel N. Fox, Michael R. Carnes
and Jim L. Mitchell

THE U.S. NAVY expends a considerable effort to determine the locations and properties of most major ocean frontal systems across the globe. This synoptic picture, called a nowcast, is partly constructed using expendable bathythermographs dropped from ships (XBTs) and airplanes (AXBTs). Such *in situ* measurements can give very detailed information, but the cost limits their utility to relatively localized and short-lived surveys. Fortunately, given an adequate database of earlier measurements, simply knowing the surface location of a front is often sufficient to reconstruct an accurate picture of the three-dimensional thermal structure of the water column to depths of thousands of meters. Obtaining that surface information is not a trivial task however.

Satellite infrared-radiometer (IR) images provide locations of important mesoscale features over large areas, but clouds can obscure important fronts for long periods, and the surface thermal structure is not always an accurate guide to the actual location of the predominant currents. An unknown geoid and other problems not withstanding (Mitchell *et al.*, 1990), satellite altimetry can provide accurate locations of currents and related features. In many areas of interest, the time and space scales on which the oceans evolve are not adequately sampled, however (Hurlburt, 1984; Kindle, 1986; Thompson, 1986). For example, the U.S. Navy's Geodetic Earth Orbiting Satellite (GEOSAT) (Born *et al.*, 1987) with its 17-day repeat cycle and equatorial track separation of less than 150 km was adequate to sample regions such as the Gulf of Mexico, but was not sufficient to provide a synoptic picture for the evolution of the Gulf Stream.

One approach to the sampling problem is to combine computer models of the oceans with data assimilation methods to extract the most information possible from the limited data available (Hurlburt, 1984 and 1992, this issue; Thompson, 1992, this issue). The design of an ocean observation, data assimilation, and forecasting system can be simplified by exploiting known characteristics of the ocean. As noted previously, the three-dimensional thermal structure of the ocean often can be reconstructed accurately given only information about fronts and eddies at the surface. Furthermore, the vertical structure of such quantities as temperature, salinity, density, and sound speed in the water column can be represented by a very small number of modes (two or three). These modes are basis functions that can be used to reconstruct the vertical profiles. Unlike arbitrary functions, such as polynomials or sines and cosines, these *empirical orthogonal functions* are derived from the thousands of profiles previously taken in the region using a method known as principal component analysis. This technique produces the smallest number of modes that are needed to reconstruct the original profiles to a user-controlled level of accuracy. The advantage of using these empirical orthogonal-function modes is that their amplitudes are related to surface properties such as dynamic height and temperature (deWitt, 1987; Carnes *et al.*, 1990). Thus, a surface measurement of sea-surface height (and ideally sea-surface temperature as well) will provide the amplitudes of the vertical modes, which in turn give us a complete vertical profile of temperature or salinity.

An example of how accurately subsurface temperature structure can be inferred from surface satellite altimeter measurements is shown in Figure 1. Finally, the shallow mixed layer at the surface is primarily driven by the interaction of the ocean with the atmosphere, which occurs on time scales very short compared with the relatively slower mesoscale meandering of fronts and propagation of rings. It is therefore possible to build a nowcast/forecast system that separates the surface mixed layer from the general circulation, which in turn can be represented by a computer model

. . . the three-dimensional thermal structure of the ocean often can be reconstructed accurately given only information . . . at the surface.

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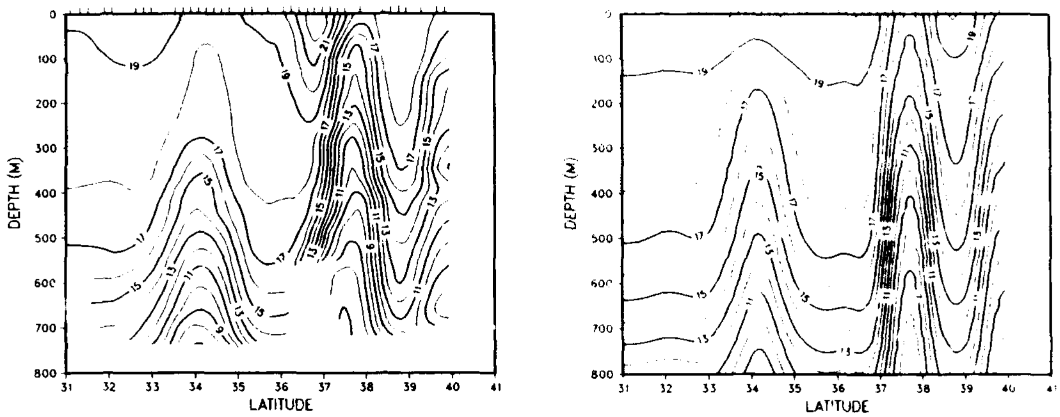

Fig. 1: Comparison of temperature measured by an airborne expendable-bathythermograph survey (left), with that inferred from a coincident Geodetic Earth Orbiting Satellite (GEOSAT) altimeter pass (right) using the synthetic data algorithms. (From Carnes et al., 1990.)

The procedure . . . begins with the subjective preparation of a Gulf Stream frontal-location map . . .

needing only a few degrees of freedom in the vertical.

A first-generation version of a nowcast/forecast system exploiting these observations has been constructed by the Data Assimilation Research and Transition (DART) group at the Naval Research Laboratory (NRL) and is now making operational forecasts of the Gulf Stream evolution for the Navy. This system has been shown (Fox *et al.*, 1992) to provide forecasts of Gulf Stream evolution that are better than persistence at both 1- and 2-week intervals, the first such system to do so using typical, operationally available data.

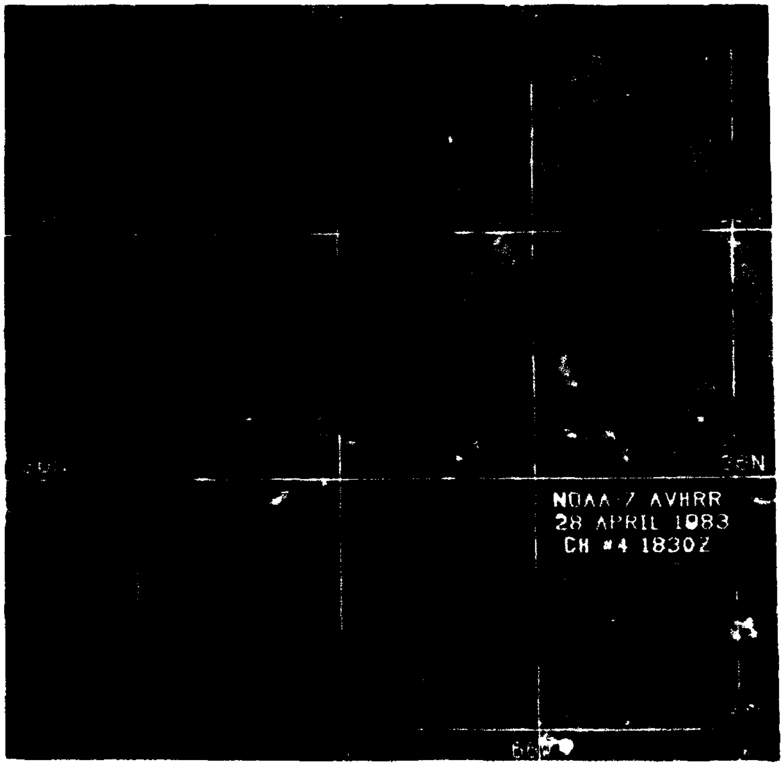

Fig. 2: Satellite infrared image for a cloud-free view of part of the ocean mesoscale field around the Gulf Stream on 28 April 1983. (From Hawkins et al., 1985.)

Estimating Initial Conditions

The procedure used to initialize and run a forecast begins with the subjective preparation of a Gulf Stream frontal-location map by the Naval Oceanographic Office. This manually prepared map blends ring- and frontal-location information obtained from satellite IR imagery (as shown in Fig. 2), satellite altimetry, and any available XBTs into a continuous depiction of the surface frontal location. On many days, portions of the Gulf Stream are obscured by clouds, so such gaps are filled using older data or previous forecasts.

The surface front and ring information is extrapolated downward into a three-dimensional thermal volume using an Optimal Thermal Interpolation System (OTIS) computer program (Clancy *et al.*, 1988; Cummings *et al.* 1991; Clancy, 1992, this issue). OTIS combines simple structural models of fronts and rings with optimal interpolation to reproduce such attributes as the sloping of the front with depth, the warm core of the Gulf Stream, and the subsurface structure of eddies.

A primary function of OTIS is to supplement real temperature observations with synthetic profiles to sufficiently resolve the mesoscale structure in the final gridded analysis. These synthetic profiles are derived from models of the Gulf Stream, its rings, and the background water structure using a front and eddy map as a guide. Most synthetic profiles are positioned in the stream, the eddies,

and in a band on either side of the stream. The distance between profiles is roughly proportional to the expected temperature-covariance length scales at each position.

OTIS assimilates the synthetic observations together with true observations to form synoptic maps using optimum interpolation (Gandin, 1963; Bretherton *et al.*, 1976). The synthetic observations provide a high-spatial-resolution data set within and near fronts and eddies, where observational data is often too sparse to resolve these features. Also, the synthetic profiles constructed from satellite surface data provide subsurface information, whereas the direct measurements made by satellites are of surface parameters only.

Dynamic height at the sea surface (used to initialize the circulation model) must be computed from the analyzed temperatures. Because salinity is not available from the OTIS analysis, dynamic heights at the surface are computed from regression relationships between dynamic height and temperature profiles. The root-mean-square error in dynamic height computed by this method is ~0.07 dynamic meters (Carnes *et al.*, 1990). Relative dynamic height at the surface is then computed directly from the grid of temperature profiles using relationships derived from analysis of regional historical temperature and salinity data sets.

Although the work described here focuses on western boundary currents (and the Gulf Stream, in particular), interest is certainly not limited to these regions. Positions of all the major fronts in the northern hemisphere are routinely determined operationally (see Fig. 3) by the Naval Oceanographic Office. We are already extending the synthetic data approach used in the Gulf Stream to the region of the Kuroshio Extension and, in a coarser implementation, to the entire world's ocean. In general, the approach of fitting satellite surface data (e.g., analyzed frontal location maps or even direct satellite measurements such as sea-surface topography from an altimeter) to low-vertical-mode temperature structure should work well in all western-boundary-current regimes. This approach seems to work at least equally well in atmospherically forced planetary-wave regimes such as the equatorial Pacific (Maul *et al.*, 1988). Recently, we have begun to examine the utility of our synthetic data approach in the more challenging regions of temperature-salinity compensated fronts (e.g., Iceland-Faroes).

Circulation Model

The circulation model used in the operational forecasts is documented in Hurlburt and Thompson (1980) and Wallcraft (1991). Applications of the model are described in Thompson and Hurlburt (1982), Hurlburt and Thompson (1984), and Thompson and Schmitz (1989). It is an n-layer, primitive-equation model covering the region from 78°W to 45°W longitude to 30°N to 45°N latitude (roughly from Cape Hatteras to the Grand Banks). It includes large-amplitude bottom topography. The model domain was chosen so that the variability in the location of the Gulf Stream entrance into the domain would be small. The version of the model used in the present system includes two layers, with a deep western boundary current (Thompson and Schmitz, 1989) supplied by an inflow port in the northeastern part of the lower layer. The model is on a spherical grid with a resolution of $\frac{1}{6}°$ in longitude and $\frac{1}{8}°$ in latitude, which represents a spatial sampling of ~14 km in each direction at the center of the grid. Because layer thickness is included among the model variables, fluctuations of the pycnocline can be modeled by changes in the depth of the interface between the upper and lower layers. This permits a more efficient representation of the dominant dynamical modes in the domain than is possible with a model that uses fixed thickness levels.

. . . the synthetic profiles constructed from satellite surface data provide subsurface information . . .

Subthermocline Initialization

Information about the subthermocline has been shown to be extremely valuable in forecasts

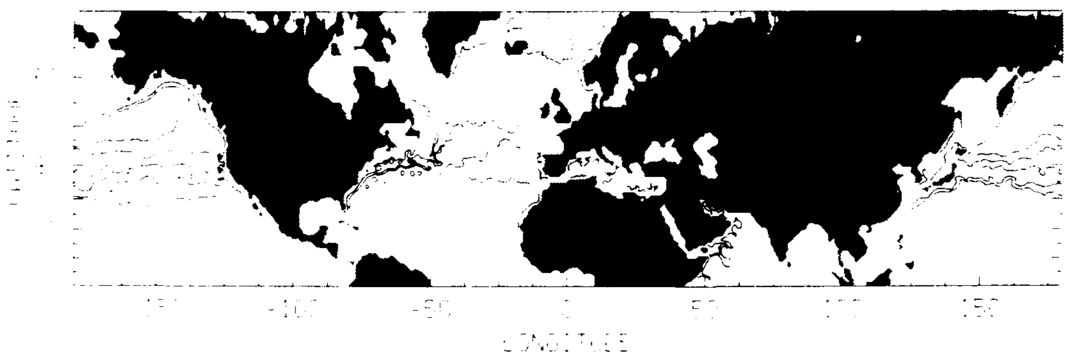

Fig. 3: A world map of many of the standard operational fronts. Positions are derived mostly from satellite infrared-radiometer imagery, which is often obscured by clouds.

based on numerical simulations of the Gulf of Mexico (Grant and Hurlburt, 1985; Hurlburt, 1986 and 1987) and the Gulf Stream (Fox *et al.*, 1988; Hurlburt *et al.*, 1990). The OTIS analysis can provide reasonable estimates of temperature in the water column, and this information can be converted into dynamic height, free-surface anomaly, or surface-pressure anomaly directly. The circulation model requires layer-thickness anomalies or (equivalently) pressure anomalies for all its dynamically active layers. Rather than attempting to extract subsurface pressure or layer thickness information directly from the OTIS analysis, we derive a statistical relationship between the surface pressure field and the pressure anomaly in the subthermocline layer. The lower-layer pressure field is only weakly correlated with the upper-layer pressure (sea-surface topography) at the same geographic location. Long model simulations are therefore used to derive statistical relationships between the subthermocline pressure at any given grid point in the model and the surface pressure at an array of grid points. To accomplish this, the model is spun up from rest for 17 model years, at which time both layers have reached statistical equilibrium as measured by the potential and kinetic energies. Five years of monthly fields are then used in the derivation of regression coefficients. Parameters that control this derivation are chosen to maximize the skill in estimating the lower-layer pressure in an independent dataset. That is, coefficients are derived from one run of the model and are used to estimate the lower layer in an independent run. In the cases of the Gulf of Mexico (Hurlburt *et al.*, 1990) and the Gulf Stream (Fox *et al.*, 1988), the lower-layer pressure anomaly from the model simulations can be accurately estimated by such techniques. The pattern correlation between upper and lower pressure anomaly is low (typically 0.2 to 0.3). The correlation exceeds 0.9 between the true lower-layer pressure fields and that estimated from the upper layer by the statistical inference technique, which uses spatial empirical orthogonal functions of the sea-surface topography as predictors. Alternate methods for initializing the lower-layer pressure field, such as using the reduced-gravity approximation (setting the pressure anomaly to zero) or climatology (setting it to the mean derived from a long circulation model simulation), produce significantly worse forecasts (Fox *et al.*, 1992).

. . . differing time scales . . . permit the separation of the prediction problem into regimes . . .

Surface Mixed Layer

A central assumption of our approach to ocean modeling has been that the differing time scales of the thin surface mixed layer and the mesoscale dynamics permit the separation of the prediction problem into two regimes that are united later. Significant progress has been made in achieving this reconnection. Experiments so far show that combining the geostrophic vertical shear (derived from the mass field of the mixed-layer thermodynamic model; Clancy, 1979, 1981, and 1983) with the surface geostrophic velocity and depth-independent ageostrophic velocity (from the circulation model) provides an advection field, which can synchronize the two models for the operationally required time period. Figure 4 shows an example of the temperature field at 200 meters from a 1-week coupled forecast.

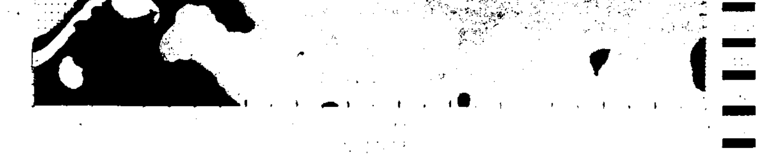

Fig. 4: Temperature at 200 meters from a 1-week run of the coupled hydrodynamic and thermodynamic computer models.

Forecast Skill

The measure chosen to evaluate the performance, or skill of the forecast system depends on the interests of the particular user. Operationally, the system was needed to forecast the absolute position of the Gulf Stream, so the measure chosen to evaluate the skill is an estimate of the average absolute offset between the true stream location and that forecast by the system. It is useful to compare the performance of the model forecast to the alternatives of persistence and climatology. In the case of persistence, we compute the error between the initial conditions and the final state 1 or 2 weeks later, without running any model forecast at all. This also is also called the assumption of no motion. In the case of climatology, the final state is compared against an average state. Figure 5 summarizes the performance of the system in the region from 73°W to 53°W longitude. The results for climatology (the uppermost, horizontal line) are computed from a year of daily analyzed Gulf Stream paths prepared at the Naval Oceanographic Office. The data is binned in $\frac{1}{2}$° increments and a mean path is computed. This average state is then compared against all the original data to compute the average offset error. Now if we are asked to estimate the location of the Gulf Stream on a day when cloud cover com-

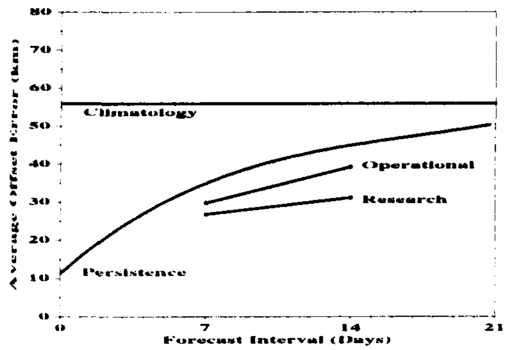

Fig. 5: Error in absolute position of the Gulf Stream using climatology, persistence, and the DART forecast system. Forecasts using 6 months of standard operational data and a small research-quality dataset are contrasted.

pletely obscures it, we could fall back on the climatological mean path, but Figure 5 shows that we will make an error of 50 to 60 kilometers by doing so.

The same data used to prepare the line for climatology can be used to estimate the results for persistence. Figure 5 shows that if the stream has been obscured for a week and we are forced to use data from 7 days ago as our estimate of today's stream location, we should expect to make an error of 35 km, on average. If we must go back 14 days to find a clear image of the stream, using this old data as our estimate of today's stream location would produce an expected error of ~45 km. It is interesting to note that the persistence curve does not pass through the origin. There are many sources of small errors in the analysis technique that are used to produce an estimate for the location of the Gulf Stream. These conspire to produce an overall error in any particular analysis of ~10 km.

Finally, we can choose to use the forecast system to project old data into an estimate of where the Gulf Stream is today. The two bottom curves in Figure 5 represent results from applying the forecast system to two different datasets. The curve labeled "Operational" is a summary of 6 months of forecast skill using the standard, operationally available Gulf Stream analyses. The curve labeled "Research" is a much smaller dataset of very high grade analyses that were prepared for the Data Assimilation and Modeling Evaluation Experiment (DAMEE) being coordinated at the Institute of Naval Oceanography. Figure 5 shows that using the forecast system with very good data produces an error of ~27 km at 7 days and 31 km at 14 days. In each case, this estimate is 20–25% better than using persistence as the forecast and far better than using climatology. Using the standard operational estimates of Gulf Stream location, the skill is still better than persistence, but not by so great a margin.

Summary

An initial version of a complete nowcast/forecast system for the Gulf Stream has been developed and successfully tested at the Naval Research Laboratory by the DART Project team, and is now used in daily Naval operations. The development of the first such system to show skill relative to persistence using routine operationally available data is a significant step toward the eventual goal of a global ocean nowcast and forecast capability.

. . . now used in daily Naval operations . . . the first such system to show skill . . . using routine operationally available data . . .

Acknowledgements

This work was supported by the Office of Naval Research, Navy Ocean Modeling Program, under program element 62435N, project 3584, block manager Robert Peloquin. Many people have contributed to this project. The authors thank Donna Blake, Jan Dastugue, John Harding, Jeff Hawkins, George Heburn, Harley Hurlburt, Joe McCaffrey, Al Pressman, Gary Ransford, Bob Rhodes, Ole Martin Smedstad, Dana Thompson, and Alan Wallcraft.

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Evaluation Capability for the Navy Ocean Modeling and Prediction Program

By John A. Leese, Robert C. Willems, and Lanny A. Yeske

THE NAVY Ocean Modeling and Prediction (NOMP) Program has emphasized the need to evaluate ocean models and prediction systems for operational and tactical applications. The Institute for Naval Oceanography (INO) was assigned a leading role in the evaluation and validation of ocean models and in providing recommendations to the Navy for adoption of models. The INO placed a high priority on this role in its efforts to design and implement an Experimental Center for Mesoscale Ocean Prediction (ECMOP) as described by Leese *et al.* (1992, this issue).

The evaluation of ocean modeling and prediction received considerable emphasis at the ECMOP Workshop (INO, 1988). The workshop recommended that guidelines be established for conducting an evaluation or determining success. It further recommended that the setting of evaluation criteria and standards be considered among the high-priority items in the early efforts of ECMOP.

Model Evaluation

The INO Summer Colloquium in 1989 initiated the development of evaluation criteria (Willems, 1989). A working group was asked to define the role of data within the context of ECMOP as a specialized facility for model evaluation. In this context, ECMOP's purpose is to provide standard data sets for model evaluation. These should fit within the framework of limited space and time resources and of limited data availability for the evaluation of mesoscale eddy-resolving models.

There are a finite number of phenomena that have observational bases from which quantitative criteria can be developed. In addition, there are few field observation programs that can be used for model evaluation as part of an oceanographic-integrity test. Guidelines need to be established to identify the existence of phenomena within a data set. In constructing criteria for phenomenological model evaluation, one can designate two main areas requiring examination: 1) physical integrity and 2) oceanographic integrity. Physical integrity considers specific properties of the model itself. How well does the model conserve mass? What are its numerical and stability characteristics? Oceanographic integrity considers the evaluation of a model relative to ocean observation. This area applies to a model's performance run solely in a simulation mode, all the way to a model's performance as part of a nowcast/forecast system.

. . . a leading role in the evaluation and validation of ocean models . . .

Data sparseness, Gaussian versus non-Gaussian statistics, and statistical assessment of events were viewed as generic problems. These must be considered in the evaluation of ocean models for mesoscale ocean nowcasting/forecasting. Incorporation of statistical procedures was recommended in the following: predictability studies; statistical comparisons (model/observations); distortion due to biased sampling; error effects on statistics; decomposition of root-mean-square-error; regional (sub-domain) evaluation; inter- and intramodel comparison (simulation properties, i.e., climate drift); and second-order statistics.

Two classes of model evaluation were considered for the standards of model performance. First was scientific evaluation with the requirement that an accuracy measure was performed using benchmark phenomena and case studies. A model then can be quantitatively assessed using agreed upon accuracy measures. The model also can be qualitatively assessed based on the inherent knowledge of the circulation in the ocean region from which the benchmark phenomena and case studies are taken. Second was operational evaluation, which

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. . . a series of experiments that began with a very simple case study . . .

is a much more demanding evaluation. Specification of climatology, input data, computer resources, manpower/skill level, and interface with other modules must be made. As a model moves through an operational evaluation, there must be routine quantitative measures of success. These are in addition to qualitative assessment of how well it performs with observational data available within the time constraints of a routine operational schedule.

Ocean Model and Prediction Evaluation Experiments

The INO recognized the need to start evaluation experiments for ocean modeling and prediction as soon as possible, to provide information and recommendations to the NOMP program about existing ocean models and to provide a learning experience for evaluating ocean prediction systems. INO is carrying out a series of experiments that began with a very simple case study in June 1990 and is evolving to the Data Assimilation and Model Evaluation Experiments during 1992.

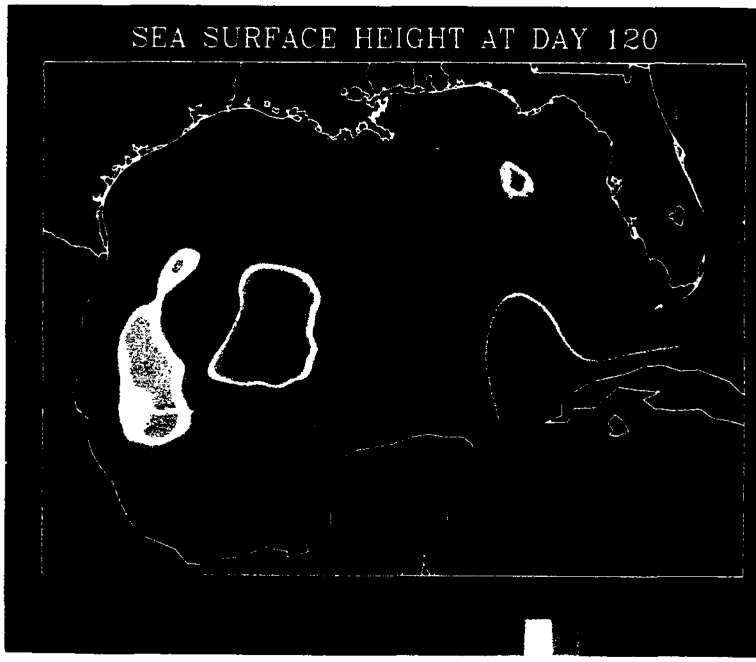

Fig. 1: TRial Ocean Prediction Experiment forecast of sea-surface height in the Gulf of Me..:o using synthetic temperature profiles derived from the Geodetic Earth Orbiting Satellite Exact Repeat Mission, conventional observations for initialization of the Princeton model and assimilation by the Derber technique. The scale ranges from −25 cm (left side) to 45 cm (right side). (Courtesy of Dr. Dong-Shan Ko.)

Results from Case Study

A nowcast/forecast system using the Princeton ocean general circulation model (Blumberg and Mellor, 1987) was adapted to the Gulf of Mexico and the Derber data-assimilation technique (Derber and Rosati, 1989) by L. Kantha and R. Passi. The infrastructure of data management, visualization, and evaluation were provided by the ECMOP facility (Leese *et al.*, 1992, this issue) to conduct a TRial Ocean Prediction Experiment (TROPE) in the Gulf of Mexico. Real data from satellite and conventional observations were used as input data (Ko, unpublished data).

The Gulf of Mexico forecast output fields (Fig. 1) were evaluated (Waters *et al.*, 1990). The evaluations used mainly the statistical techniques that were formulated from the Colloquium on Model Evaluation Criteria and that were implemented as a verification and evaluation module in ECMOP (Anand *et al.*, 1991).

The primary emphasis of TROPE has been a software engineering-type evaluation. This successfully proved the validity of the ECMOP concept to provide a specialized off-line computation center to facilitate the development, demonstration, and evaluation of a mesoscale ocean prediction capability. A number of scientists made use of the TROPE nowcast/forecast system and the output fields to conduct further analysis and evaluations. A specific example is the work of Lewis *et al.*, (1991) to evaluate the movement of eddies by the Primitive Equation Data Assimilating Model (PEDAM) in the Gulf of Mexico.

An Ocean Nowcast/Forecast Experiment

The results from the ECMOP Workshop (INO, 1988), along with preparatory work for the Colloquium on Model Evaluation Criteria (Willems, 1989), brought forth an interest among several modeling groups to conduct an assessment experiment in ocean modeling and prediction. INO hosted a separate meeting after the Colloquium to consider a proposal for a nowcast/forecast assessment experiment during 1992. There was a consensus at the meeting that it was particularly timely to conduct such an assessment experiment with the following general characteristics:

Objective: To estimate the state-of-the-art for data assimilation and nowcast/forecast production, using the primitive-equation ocean general circulation model.

Data period: 1987–1988.

Geographical area: Within the region bounded by 25°–45°N latitude and 40°–80°W longitude.

Scenarios: Case studies (up to 10) where data quality and quantity were sufficient.

Participants: Modeling groups working in the North Atlantic Region.

The term assessment means, in general, the evaluation of objectively analyzed and short-term forecast fields to determine how well they describe the real ocean at the valid times and, to the extent possible, to determine the effects of input data, the data-assimilation techniques, and the performance of the ocean circulation model.

The INO agreed to coordinate experiment planning and design, provide infrastructure facilities through the ECMOP facility, assist modeling groups in conducting experimental runs, and complete arrangements for meetings and workshops. The INO has worked, since the August 1989 meeting, with the NOMP Program Manager and the ocean modeling groups working in the Northwest Atlantic region to coordinate the planning and design of the nowcast/forecast assessment experiment. A number of modeling groups provided assistance in the planning and design for the nowcast/forecast experiment and are now participating in the experiment:

a. Group led by A. Robinson, using the Harvard open-ocean model as a basis for an ocean nowcast/forecast system known as FLEXCAST;

b. Group led by P. Rizzoli (Massachusetts Institute of Technology) and D. Haidvogel (Rutgers University), using a nowcast/forecast system based on the Semi-Spectral Primitive Equation Model (SPEM);

c. Group led by G. Mellor, using the Princeton model as a basis for a nowcast/forecast system known as PEDAM for the Gulf Stream;

d. Group led by D. Fox, using a nowcast/forecast system based on the NRL primitive equation (PE) model and referred to as Data Assimilation Research and Transition (DART).

The geographical boundaries used by each of the modeling groups is shown in Figure 2. Model attributes are shown in Table 1. The design of the numerical models was determined, implemented, and verified independently and prior to this nowcast/forecast experiment (see Blumberg and Mellor, 1987; Robinson *et al.*, 1988; Haidvogel *et al.*, 1991). Clearly, similarities and differences exist in methodologies and design. Numerical solution methods; surface, lateral, and bottom boundary specifications; and mixed-layer representation (whether resolved or not) are dealt with differently in the various models. Table 1 articulates the more substantial differences to be considered in developing model evaluations. The infrastructure facilities of data management, visualization, and evaluation are being prepared by the ECMOP project in INO led by J. Corbin. A data group, led by S. Glenn (Rutgers University), prepared the research-quality data sets needed to conduct the experiment.

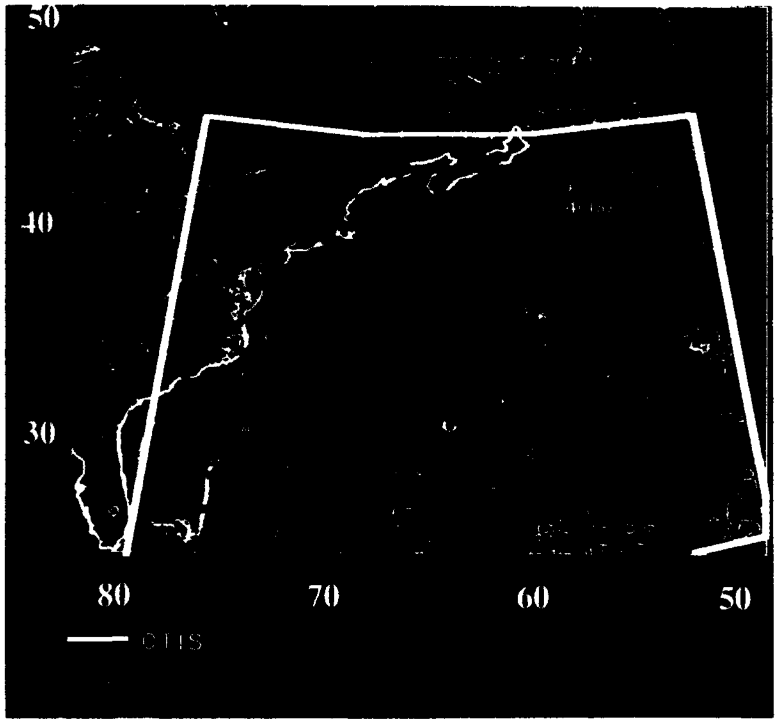

Fig. 2: Optimal Thermal Interpolation System (OTIS 3.0) and ocean model domains for the Data Assimilation and Model Evaluation Experiments in 1992.

Table 1
Ocean model attributes

Model	Numerical Solution Method	Surface Boundary Condition	Vertical Coordinate Specification	Mixed Layer	Lateral Boundary Condition	Bottom Boundary Condition
SPEM	Implicit	Rigid lid	Sigma level Chebyshev polynomials	No	Coastline/open boundary	Smoothed topography
PEDAM	Implicit	Free surface	Sigma level	Yes Mellor-Yamada closure scheme	Coastline/open boundary	Smoothed topography
FLEXCAST	Implicit	Rigid lid	Sigma level	No	Open boundary	Smoothed topography
DART	Semi-implicit	Free surface	Layer/reduced gravity	No	Coastline/open boundary	Smoothed topography

. . . assess the impact of several data-assimilation techniques on the various models using the same case-study data.

The Navy has recently completed an evaluation of two ocean circulation models as components of the Naval Operational Gulf Stream Forecast System (NOGUFS). The case studies used for the evaluation were during data-rich periods. Some of the cases contained ambiguities in the analyses of Gulf Stream and ring locations (due to clouds, etc.), as determined from the Advanced Very High Resolution Radiometer (AVHRR). A re-analysis was performed to prepare research-quality data sets (Glenn *et al.*, 1991). From this re-analysis, six case studies were identified for the assessment experiments.

Pre-Experiment Tests in 1991

A pre-experiment to quantify the forecast capability of an ocean model was conducted in 1991 and involved initializing an ocean model domain that was configured for the Gulf Stream region. The temperature, salinity, and sea-surface height fields were prepared using the Optimal Thermal Interpolation System (OTIS), which is currently being used by the Navy (Clancy *et al.*, 1990). Figure 3 is an example of the temperature field at 500 m. At 1- and 2-week intervals, the model forecast position of the north wall of the Gulf Stream was compared with the observed position. The best comparison was with the position determined from the National Oceanic and Atmospheric Administration (NOAA) satellite image available at the end of each case study.

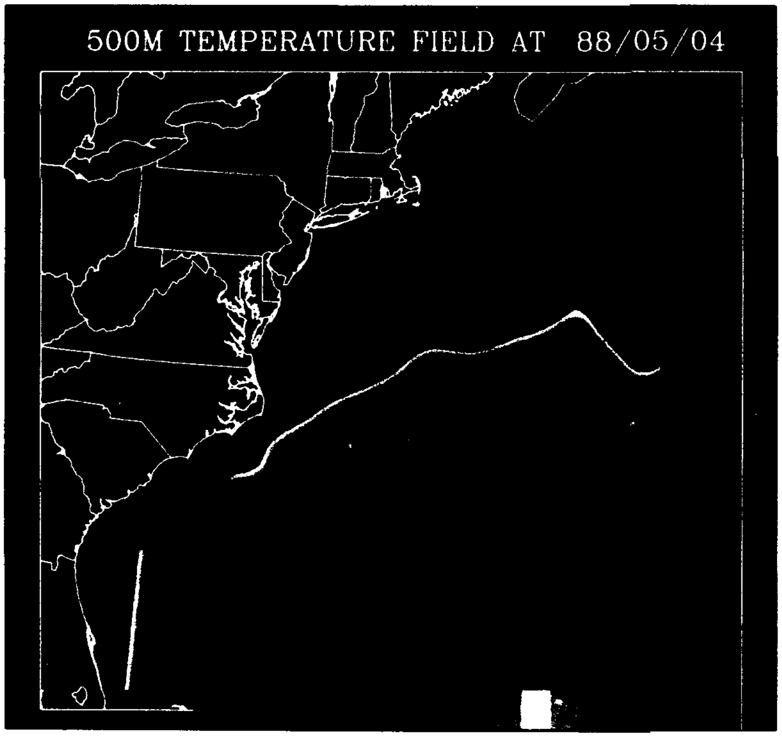

Fig. 3: Optimal Thermal Interpolation System (OTIS) 3.0 temperature field at 500 meters for 4 May 1988 as applied to the Princeton model domain in the Gulf Stream (for the 1991 preexperiment). Advanced Very High Resolution Radiometer analysis of the stream position and warm/cold eddy locations, climatology, and conventional observations are input to the calculation of OTIS fields. The scale ranges from 5°C (left side) to 18°C (right side). (Courtesy of Dr. Dong-Shan Ko.)

Data Assimilation and Model Evaluation Experiments in 1992

The Data Assimilation and Model Evaluation Experiments (DAMEÉ) are being carried out in 1992. This is a follow-on to the 1991 pre-experiment tests and will assess the impact of several data-assimilation techniques on the various models using the same case-study data. Additionally, two month-long case studies are identified, wherein one has meandering characteristics and the other has a ring formation/pinchoff or ring coalescence. The data available for assimilation and verification are the NOAA satellite infrared images, Airborne Expendable Bathythermograph (AXBT), Expendable Bathythermograph (XBT), Multi-Channel Sea-Surface Temperature (MCSST), and Geodetic Earth Orbiting Satellite (GEOSAT) Exact Repeat Mission sea-surface height. OTIS 3.0 fields from the six case studies are available as a data set as well. These case studies occur when the GEOSAT satellite provided useful sea-surface height data and also during the Synoptic Ocean Prediction (SYNOP) observational period. The assessment will be conducted in four phases, each based on different data sets from the case studies and building upon the results from previous phases.

Quantitative measures of ocean-model performance with data assimilation are relative to persistence and using forecast positions of the Gulf Stream, compared with a best-available analysis position produced by AVHRR on the forecast day at the end of each week.

Concluding Remarks

The progress in developing and implementing an ocean modeling and prediction evaluation capability for NOMP has evolved over the last two years. This capability is now being combined with the ECMOP Modular System in the INO to provide a special purpose facility. The Data Assimilation and Model Evaluation Experiments in 1992 will serve as a good test of the overall concepts that provided the basis for the design and implementation of this facility.

Acknowledgements

The INO is preparing the ocean modeling and prediction evaluation capability for NOMP with the very capable assistance of experts from the ocean modeling community. We particularly acknowledge the assistance received from all the participants at the 1989 INO Summer Collo-

quium on Model Evaluation Criteria. We also acknowledge the contributions from the modeling groups participating in the Ocean Modeling and Prediction Evaluation Experiments being coordinated by the INO.

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AN EXPERIMENTAL CENTER FOR MESOSCALE OCEAN PREDICTION

By John A. Leese, M. Stephen Foster
and James H. Corbin

. . . a sophisticated data-base management system is a high priority . . . in a numerical ocean modeling and prediction system.

THE NEEDS of the naval and academic community to expand their modeling activities were identified in an Ocean Prediction Workshop during 1986 (Mooers *et al.*, 1986): 1) an openly shared hierarchy of well-documented models; 2) direct access to computational resources; 3) improvement of scientist-to-scientist communications through standardized procedures for model testing and validation; and 4) various kinds of certified data sets. The Institute for Naval Oceanography (INO) response to these needs was to implement an Experimental Center for Mesoscale Ocean Prediction (ECMOP). This is a specialized computational center to facilitate the development, demonstration, and evaluation of a mesoscale ocean-prediction capability.

An early planning study (INO, 1988) investigated the functional components of an experimental center. This study concluded that the best overall strategy for ECMOP was to take advantage of the infrastructure provided by the Naval Oceanography Command for real-time operations and to provide capability for validation and evaluation of ocean models. Another feature was a conceptual design for ECMOP. The major functions within the framework of a numerical ocean prediction system should be structured with sufficient modularity to provide flexibility for modification as needed to conduct evaluation of ocean modeling and prediction. Figure 1 depicts the major features of such a modular prediction system (INO, 1988). This figure shows the many places where different data sets are needed or accumulated. It also shows clearly why a sophisticated data-base management system is a high priority for early implementation in a numerical ocean modeling and prediction system.

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Experimental Center for Mesoscale Ocean Prediction as a Specialized Facility

ECMOP has set three major long-term goals:

1) provide the infrastructure and support needed for research and development in ocean modeling and prediction. The emphasis is on data management, visualization, and evaluation;

2) adopt the technology and methodology in these areas for applications in operational ocean predictions; and

3) continue to update the technology and methodology for the scientific community.

To establish a high-quality, wide-spectrum data base and software library for the oceanic modeling community, ECMOP has adopted two paradigms. ECMOP will use existing data in the National Oceanic and Atmospheric Administration (NOAA) and the Navy archives so that the ECMOP resources can be concentrated on establishing special data sets for research and evaluation of ocean modeling and prediction. ECMOP will create incentives for investigators to submit their data to the data pool. The chief benefit to contributors is the use of the data sets contributed by other investigators.

An ECMOP User Support and Model Library will place heavy dependence on sources outside ECMOP. To take advantage of the many potential sources of software and achieve a cost-effective service, ECMOP will classify several different levels of applications software and models in the library. The user support, including documentation and user guides, will be according to the classification level for each of the software items. A scientific and technical advisory group has been formed to provide advice and assistance.

Evolutionary Development of the Experimental Center for Mesoscale Ocean Prediction

An early objective for ECMOP was to develop, demonstrate, and evaluate an initial ocean-prediction system based on existing capability. Stability and flexibility were needed to provide a

learning experience and to demonstrate the validity of a specialized facility for evaluation of ocean model and prediction systems. Our design for a case study took the modular concept, previously shown in Figure 1, and applied state-of-the-art technology in data-base management. Together with existing components for each of the modules, a system was constructed and named the Primitive Equation Data Assimilating Model (PEDAM). The ocean model was specifically configured for the Gulf of Mexico (GOM).

The ECMOP/PEDAM (GOM) ocean prediction system is depicted schematically in Figure 2. A four-dimensional data-assimilation scheme (Derber and Rosati, 1989) was combined with the Princeton ocean general circulation model (Blumberg and Mellor, 1987) and was applied to the Gulf of Mexico by Drs. L. Kantha and R. Passi at the INO. An initial set of statistical and physical measures based on the results of the Model Evaluation Criteria Colloquium (Willems, 1989) was used to form the Verification Module (Anand *et al.*, 1991). The data management portion of the system was comprised of a proprietary data-base management system and the Naval Environmental Operational Nowcast System (NEONS). The National Center for Atmospheric Research (NCAR) Graphics package was employed to fulfill visualization objectives.

Real data in the form of conventional expendable bathythermograph (XBT) observations, along with satellite-derived sea-surface temperature and sea-surface height measurements derived from the Geodetic Earth Orbiting Satellite (GEOSAT) altimeter data for the period November 1986 to April 1987, were used as input data to PEDAM (Ko, unpublished observations). Model output fields were evaluated in both nowcast and hindcast modes (Waters *et al.*, 1990). The case study clearly demonstrated that users of this specialized facility could exploit the system's capabilities after a short orientation period.

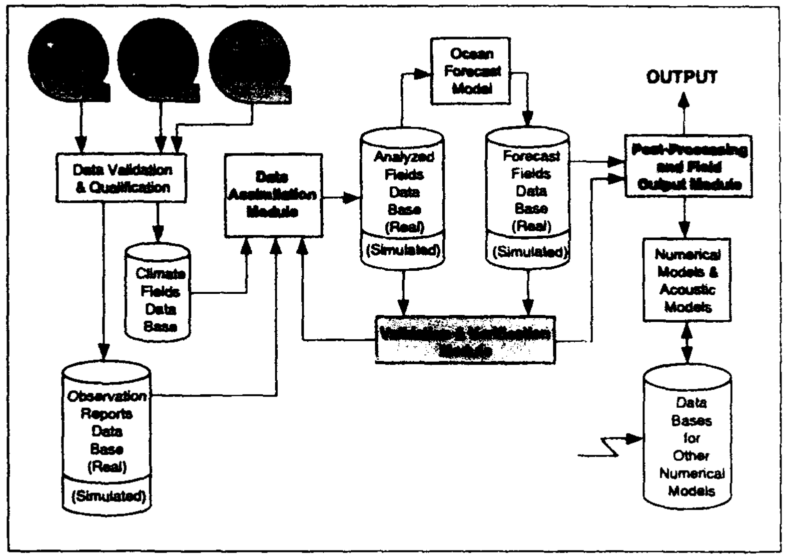

Fig. 1: Components of an ocean prediction system depicting input data and ocean model output fields as separate entities.

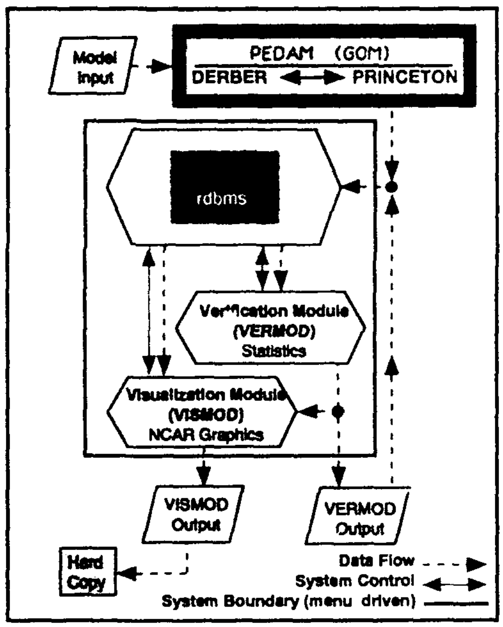

Fig. 2: Modular flow diagram for the ECMOP system as configured during 1990 for the Primitive Equation Data Assimilation Model (PEDAM) case study for the Gulf of Mexico (GOM). The PEDAM case study successfully demonstrated the utility of the ECMOP modular concept in constructing a system for assessing ocean model performance and displaying the output. Control linkage was weak at this early stage in system development.

A Prototype Modular System

The lessons learned from the ECMOP case study were incorporated into a PROTotype ECMOP Modular System (PROTEMS). The major focus of the PROTEMS is a graphical-user interface that gives both the user and the designer greater flexibility but still maintains ease of learning and use. The primary function of PROTEMS is to access data sets (historical, climatological, etc.) for visualization or evaluation.

PROTEMS facilitates a single package solution to the problem of mastering the details of numerous software applications during model development and assessment. All the necessary development tools have been made available through a graphical-user interface. All software elements within PROTEMS have one critical factor in common—their ability to interface with the C and Fortran programming languages. Currently, there are three principal modules (Fig. 3) within PROTEMS: 1) the Data Management Module

The primary function . . . is to access data sets . . . for visualization or evaluation.

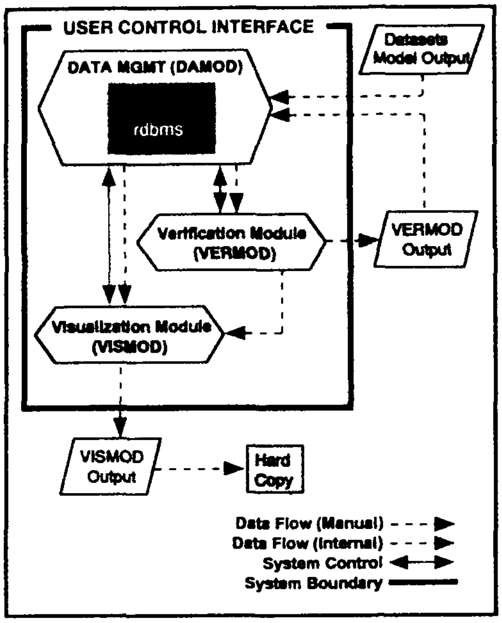

Fig. 3: The Prototype ECMOP Modular System (PROTEMS) as currently implemented. A Graphical User Interface (GUI) has been added, which interprets and acts upon user commands and which controls internal data flow. Future plans include addition of an acoustics module, a data browser and, most importantly, extension of the GUI to incorporate linkage with an ocean model and control of module output.

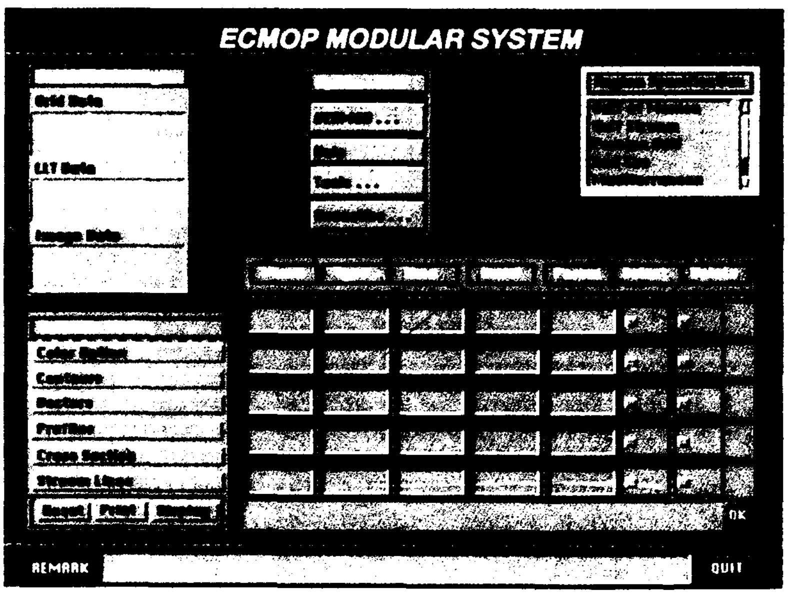

Fig. 4: Initialization screen for PROTEMS (current implementation). User interaction begins in the upper right corner with selection of a region. Region selection initiates a search of the data base for data types appropriate to the selected region. The data types are listed in the box at the upper left for user selection. Those data sets selected by the user are then displayed in the matrix at lower right for further parameterization. When this step is completed, the user may pass the data to VERMOD (verification module; top center) or exercise the graphics choices shown at lower left.

(DAMOD); 2) the Verification Module (VERMOD); and 3) the Visualization Module (VISMOD). These modules, when interfaced with a user-supplied ocean model and a data-assimilation technique, comprise an ocean prediction system. The INO-designed graphical-user interface (Fig. 4) upgrades the original menu-driven version developed for the PEDAM (GOM) case study.

Users indicate their data requirements to the DAMOD by selecting the geographical region, model type, physical parameter(s), levels, and time period from the opening display screen and subsequent "pop-up" displays. Selections are made with a "mouse" input device. These straightforward, highly visual steps require minimal skill even for an inexperienced computer user. As many as five separate data groups may be chosen before invoking evaluation or graphics options.

Assessment of ocean model performance is the principal justification for PROTEMS. VERMOD statistical tools currently require data in grid format. VERMODs root-mean-square-error capability accommodates weighting functions and employs a widely accepted derivation (Wilmot *et al.*, 1985) for its decomposition into systematic (bias) and unsystematic (exactness) error components. Other standard statistical routines include pattern correlation, skewness, and kurtosis.

Visual display of model output and derivative data give the ocean modeler a clearer understanding of model behavior. VISMOD presently supports production of contour and vector plots with geographical overlay and labeling, vertical cross-sections, and animated display. VISMOD also supports user-selectable color options and contour intervals. Geographic background selection is dependent upon the model type specified to NEONS. Figure 5 is typical of VISMOD graphical output, which may be obtained for any grid-based data structure within NEONS, including VERMOD output. Other examples are presented by Leese *et al.* (1992, this issue).

During 1992, PROTEMS will be given a thorough exposure and evaluation when it is used to support the Data Assimilation and Model Evaluation Experiments (DAMEÉ). Several different modeling groups will conduct identical case studies and compare the results using PROTEMS.

Future Plans of the Experimental Center for Mesoscale Ocean Prediction

In keeping with the long-term goal of ECMOP, some portion of the ECMOP staff will be involved in researching, developing, and implementing capabilities into the ECMOP Modular System (EMS), to maintain a facility at the leading edge of science and technology. Direct interaction with ocean models will be the primary objective of upgrades to PROTEMS needed to achieve the operational version, EMS 1.0. PROTEMS provides only two-dimensional representations; EMS 1.0 will provide three-dimensional representations, as

well as direct interaction with two-dimensional data displays. In addition, EMS 1.0 will give the scientist easy access to a full range of modeling support applications directly from a graphics terminal or workstation. The user will be able to devote maximum time to model evaluation and fine tuning because EMS 1.0 will provide the rest.

The focus will continue to be on compiling data sets needed for Navy ocean-modeling research and operations. By 1993, the ECMOP plans to compile a verification data set for the North Atlantic Basin covering the useful data period from 1986 to 1989 of the GEOSAT satellite. The compilation of a global-ocean verification data set should begin by 1995.

The ECMOP facility will contain a library of ocean models/modules with varying types of support. Some models/modules will be used routinely by a major segment of the user group and will be fully documented and maintained by ECMOP. Others, with narrower applicability, will have shared support between ECMOP and the originator. Those models/modules used only by a specific investigator may be present in the library with support provided by the investigator.

ECMOP is intended to meet the common research-support needs of a broad segment of the modeling community. Additionally, substantial improvement can be expected in the transition to operational users if the same methodology and technology are used (as much as possible) by those that develop and those that use the models. This has been accomplished with transition of a prototype version of the system to the Naval Oceanographic Office.

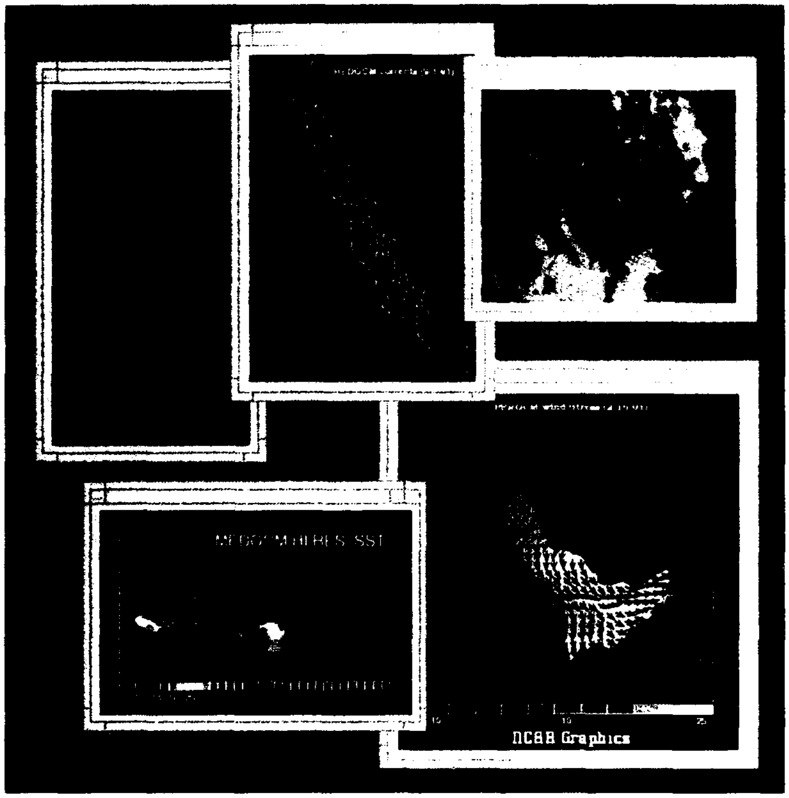

Fig. 5: Several examples of graphical output from the ECMOP visualization module demonstrating the flexibility for data-base control of model output geometries and satellite image enhancement possibilities.

Acknowledgements

We thank J. Hovermale and T. Tsui from the Atmospheric Directorate of NRL for providing their NEONS software to enable INO to get an accelerated start on the ECMOP modular system: V. Anantharaj, H. Anand, and R. Krishnamagaru for their extra efforts in getting the early versions of the ECMOP Modular System completed; and all the participants at the 1988 ECMOP Workshop.

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Sea Ice Prediction: The Development of a Suite of Sea-Ice Forecasting Systems for the Northern Hemisphere

By Ruth H. Preller

THE LAYER of ice and snow that covers the Arctic Ocean and its marginal seas is highly variable in nature. Satellite imagery of the ice cover (Parkinson, 1991) has shown great interannual variability in the monthly averaged sea-ice distribution over the past 15 years. Although the central Arctic has its greatest variability in the summer, many of the marginal seas, which are ice covered in winter only (e.g., Bering Sea and the Sea of Okhotsk), exhibit the greatest variability in winter. The seasonal cycle of ice growth and decay has also been observed to vary from region to region and from year to year (Parkinson *et al.*, 1987). On average, the ice cover in the northern hemisphere reaches its maximum extent in March and its minimum extent in September.

. . . accurate forecasts of the variability of sea-ice conditions . . . can provide valuable information to both naval and commercial operations.

The variability in the extent of the ice cover is due to a number of different forces acting on the ice. Heating and cooling from both the atmosphere and the ocean are responsible for the growth and decay of sea ice. In addition, the ice cover, with the exception of shorefast ice, (ice attached to the shore) is in a state of nearly constant motion and deformation. Deformation of the ice causes the formation of ridges, leads, ice rubble, and ice floes.

The variability exhibited by the polar oceans exerts a strong influence on global climatology. In winter, the ice cover acts as an insulator limiting the heat exchange between the cold atmosphere and the relatively warm ocean. In summer, the ice cover reduces the total solar heating of the earth's surface by reflecting four to seven times the amount of solar radiation reflected by open water (Parkinson *et al.*, 1987). Feedbacks among surface albedo, ice extent, snow cover, and the global heat budget are crucial in the determination of global climatology.

On shorter time scales, accurate forecasts of the variability of sea-ice conditions in the polar oceans can provide valuable information to both naval and commercial operations. Ships and field operations benefit by knowing the thickness of the ice, the movement of the ice (ice drift), and the location of the ice cover (versus open water).

The Navy/National Oceanic and Atmospheric Administration (NOAA) Joint Ice Center (JIC) located in Suitland, MD, is actively engaged in global sea-ice analysis and forecasting. Most of the JIC's users are either commercial or Navy fleet operators who require ice-edge information during the course of operations. In response to the need of these users, the JIC creates both a 7-day forecast of ice-edge location and a weekly ice-concentration (percentage of ocean area covered by sea ice) analysis. The ice-concentration analysis is derived mainly from satellite data. In addition, numerical models are providing products, such as forecasts of ice drift, that are used as guidance by the JIC in determining the 7-day forecast of change in the ice-edge location.

Numerical Models of Sea Ice

Our understanding of the dynamics and thermodynamics of sea ice has increased substantially over the past 20 years. Observational data from field experiments, such as the Arctic Ice Dynamics Joint Experiment (AIDJEX) and the Marginal Ice Zone Experiment (MIZEX), and remotely sensed data have provided enough information to design some very sophisticated models of the behavior of sea ice. Various types of ice models—dynamic, thermodynamic, and dynamic-thermodynamic—have been developed and applied to both the Arctic and Antarctic.

The simplest dynamic ice model, used to determine ice motion, is based on a balance of forces between wind and water stresses and the Coriolis force. This "free drift" model is often a good approximation away from boundaries and under divergent conditions. However, ice drift may be adjusted significantly in both magnitude and direction by internal ice stress. Near coastlines and in regions where convergence is taking place, stress

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on the ice can cause ridging and ice deformation to occur. Models that include internal ice stress contain a constitutive law that treats ice as a viscous, elastic, viscous-plastic, or elastic-plastic medium. Most ice models make the assumption that ice acts as a continuum, a continuous medium, not as a field of individual floes. Although this assumption may be valid in the central Arctic, it is not very useful in the marginal ice zone (e.g., the Greenland Sea). Research to develop more accurate, realistic ice rheologies is an ongoing effort.

Thermodynamic ice models address the evolution of the mean ice/snow thickness based on the combined effects of atmospheric heat fluxes and oceanic heat fluxes. These heat fluxes are transported in the snow/ice layer by conduction. The surface heat balance consists of shortwave radiation, modified by the effects of albedo, incoming and outgoing longwave radiation, sensible heat flux, and latent heat flux. The oceanic heat flux is the amount of heat added or removed from the ocean's mixed-layer, which lies directly beneath the ice cover. Heat is added or removed from this layer by horizontal advection or by heating from beneath the layer.

Dynamic-thermodynamic models integrate the important effects of ice motion and ice growth/decay into one model. Most of these ice models use constant or prescribed ocean currents and heat fluxes. However, to accurately predict the variability of the ice-edge location, it is necessary to provide the appropriate variability in the ocean forcing. This has been done by coupling dynamic-thermodynamic ocean models to the ice models.

U.S. Navy Sea Ice Forecasting Systems

Over the past 7 years, the Naval Research Laboratory (NRL) has undertaken the design of operational sea-ice forecasting systems capable of providing guidance products to the JIC for the Arctic and its subregions. At the center of these forecast systems is a numerical sea-ice model.

Three such forecast systems are run operationally at the Fleet Numerical Oceanography Center (FNOC) located in Monterey, CA. The first system to be developed, the Polar Ice Prediction System (PIPS), encompasses the central Arctic basin, the Barents, and the Greenland Seas (Fig. 1). The two more recent systems are higher-resolution regional versions that encompass a particular basin. The Regional Polar Ice Prediction System—Barents Sea (RPIPS-B) covers the Barents Sea and the western part of the Kara Sea, as well as the White Sea. The Regional Polar Ice Prediction System—Greenland Sea (RPIPS-G) covers the region adjacent to the east Greenland coast. PIPS uses a grid resolution of 127 km, RPIPS-B uses 25 km, and RPIPS-G uses 20 km.

Each of these forecast systems has the same basic design (Fig. 2) centered around a dynamic-thermodynamic sea-ice model (Hibler 1979 and 1980). The model has the ability to determine ice drift, thickness, and concentration (including the location of the ice edge). It consists of five major components: 1) momentum balance, which includes wind and water stresses, the Coriolis force,

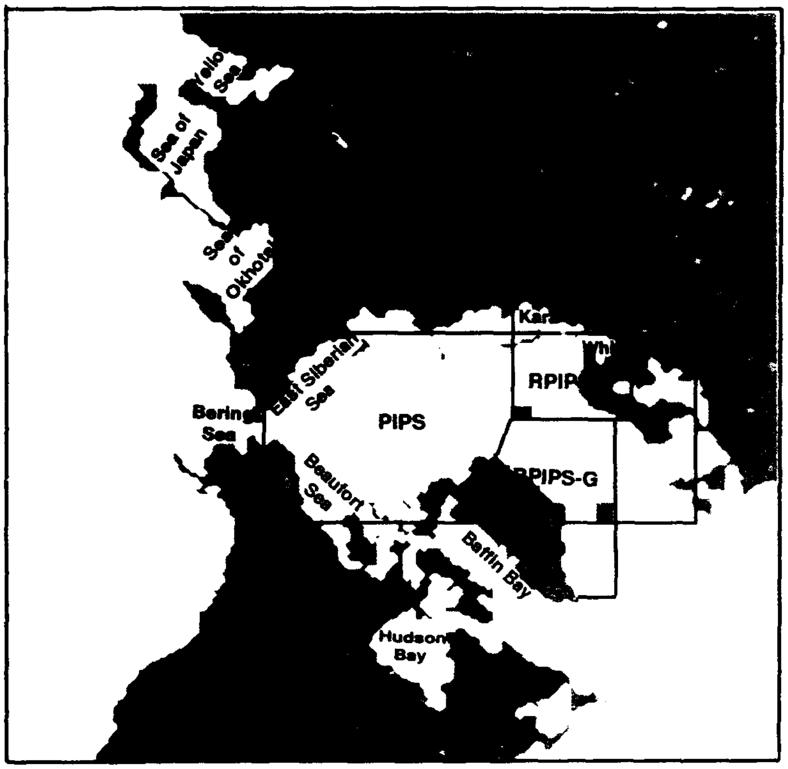


Fig. 1: The region covered by the Polar Ice Prediction System (PIPS) 2.0 forecast system with the boundaries of the PIPS, the Regional Polar Ice Prediction System—Barents Sea (RPIPS-B), and the Regional Polar Ice Prediction System—Greenland Sea (RPIPS-G) domains included.

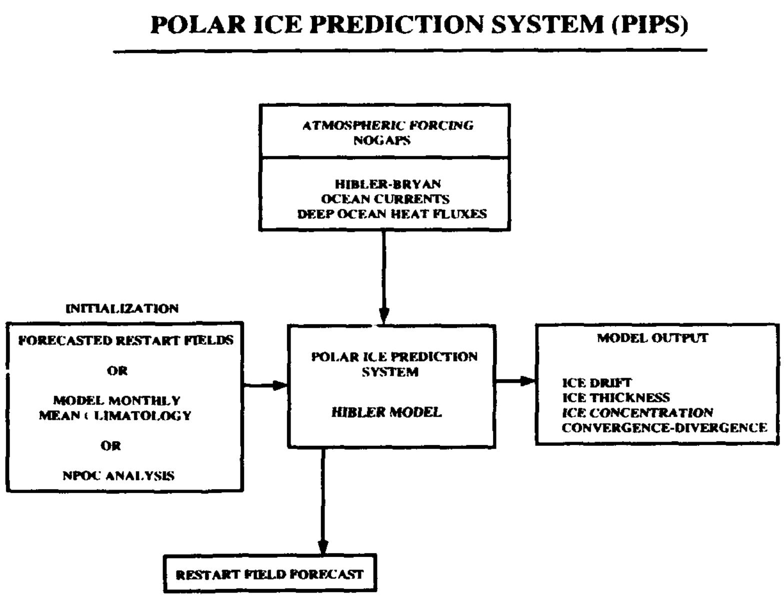
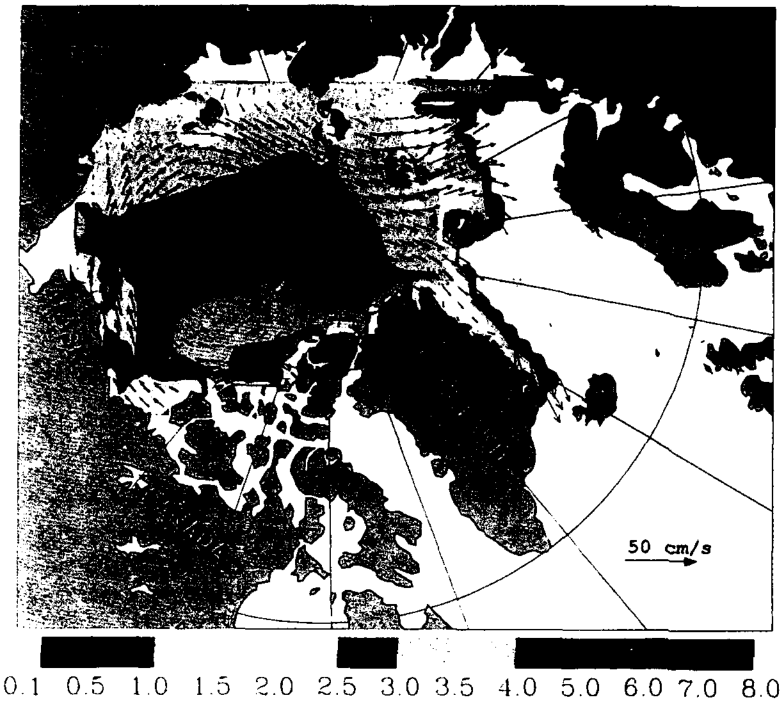


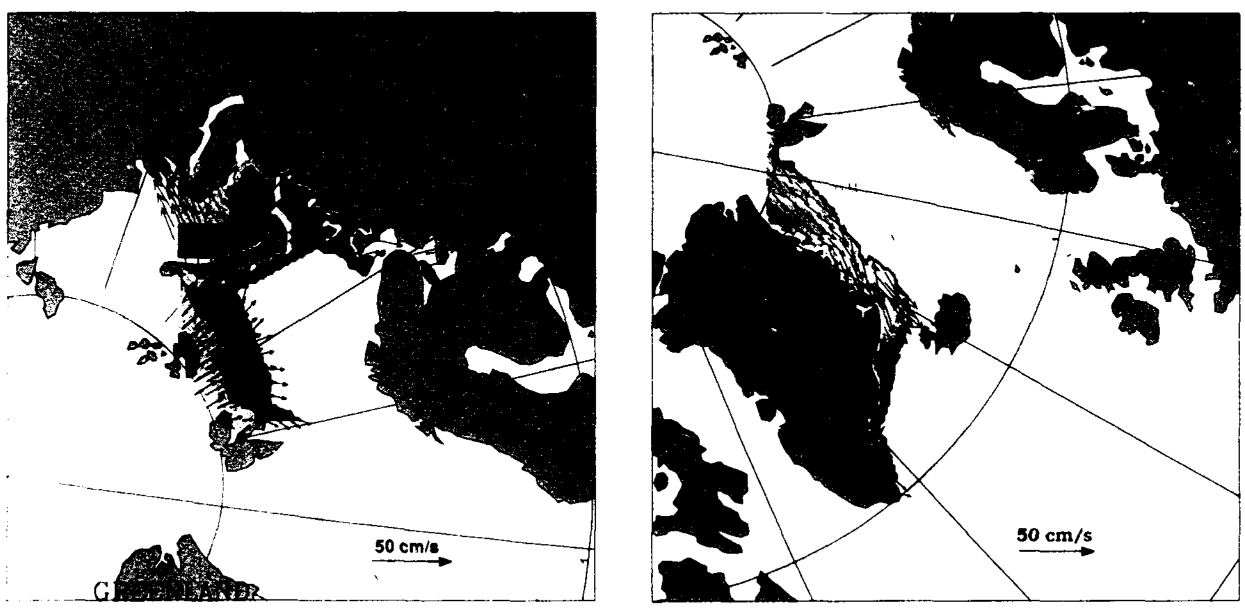
Fig. 2: A schematic of the design of the PIPS and RPIPS forecast systems.

and inertial forces; 2) ice rheology, relating ice stress to ice deformation; 3) ice-thickness distribution; 4) ice-strength formulation; and 5) atmosphere-ice-ocean heat budget. The Navy's atmospheric forecast model, the Navy Operational Global Atmospheric Prediction System (NOGAPS) (Hogan *et al.*, 1991) provides the necessary atmospheric forcing (i.e., the winds, surface air temperatures, and atmospheric heat fluxes) needed to drive the ice model. Oceanic forcing is specified in the form of monthly mean ocean currents and heat fluxes derived from a coupled ice-ocean model (Hibler and Bryan, 1987). The forecast systems are used to make a 120-hour forecast each day. The ice model is initialized daily from the previous day's 24-hour forecast. The regional models also require ice-thickness information from PIPS to serve as ice-inflow boundary conditions at the open boundaries (Preller *et al.*, 1989). If for any reason the 24-hour forecast is not available, each model is initialized from a model-derived monthly mean climatology.

Once each week, the model's ice concentration is initialized from observations. The ice-thickness fields and ocean temperatures are adjusted at the ice edge to agree with the observations (Preller and Posey, 1989), which are a digitized form of the JIC ice-concentration analysis. This analysis is derived from a number of different sources of satellite data: infrared imagery comes from the Advanced Very High Resolution Radiometer (AVHRR) on board the NOAA polar-orbiting satellite; visible-band imagery is obtained from the Defense Meteorological Satellite Program's (DMSP) Optical Line Scanner (OLS) operated by the U.S. Air Force; and passive microwave data (brightness temperatures) comes from the Special Sensor Microwave Imager (SSMI) carried on board the DMSP "morning" satellite. In addition to this, available data from ice reconnaissance flights or ship observations are included (Wohl, 1991). Recently, SSMI ice-concentration data have become available in real time at FNOC.



A



B

C

*Fig. 3: The 24-hour forecast fields of ice thickness and ice drift from May 9, 1991 for (A) PIPS, (B) RPIPS-B, (C) RPIPS-G. Color bar indicates the ice thickness in meters and the scale vector for ice drift is 50 cm/sec. **B** and **C** use the same color scale.*

Table 1
Daily products available from each of the three Navy sea-ice forecast systems

Field	Forecast Time, hr
Ice Drift	24, 48, 72, 96, 120
Ice Thickness	0, 120
Ice Concentration	0, 120
Divergence/convergence	48, 96, 120
Ice thickness difference	120
Ice concentration difference	120
NOGAPS surface pressure with winds	0, 120

Work is presently underway to examine SSMI data for possible daily model initialization purposes.

Forecast System Products

A set of 14 products is saved from the 120-hour forecast made daily by each forecast system. The fields listed in Table 1 are provided to the JIC to be used as guidance products. Two additional NOGAPS fields, surface pressure with surface winds overlaid, are sent along with the ice products.

Figure 3, A–C, are examples of model-derived 24-hour forecasts of ice thickness and ice drift. This time of year is representative of late-winter conditions in the Arctic. The ice-thickness distribution forecast by PIPS is similar to that seen in under-ice submarine data (Hibler, 1979; Bourke and Garrett, 1987). The average forecast for ice thickness in the central Arctic is from 2.5 to 3.0 m. The thickest ice ($\geq$6.0 m) is found along the Canadian Archipelago, and the thinnest ice is found in the marginal seas. A high pressure system is responsible for the clockwise ice drift, which dominates the Arctic basin. Ice flows southward through the Fram Strait into the Greenland Sea and southward from the central Arctic into the Barents Sea.

The regional forecast systems were developed to provide better resolution of sea-ice conditions near land boundaries and at the ice edge. Similar thickness and drift patterns exist in the regional systems, but with more detail visible in the results, particularly near land boundaries and at the ice edge. RPIPS-B extends into the Kara and White Seas, providing forecasts for these regions not covered by PIPS. Although the general ice-edge pattern forecast by these two systems is similar (e.g., both forecast the southern half of the Barents to be ice free) due to the higher resolution of the ice model, greater detail is found in the RPIPS-B ice edge. A similar situation exists in RPIPS-G, which extends farther south than PIPS, providing ice information south of the Denmark Strait. Similar to the PIPS versus RPIPS-B comparison, the ice edge of RPIPS-G has the same general features as PIPS but with a more highly resolved ice-edge location.

Future Plans for Sea Ice Forecasting Systems

The next-generation ice forecasting system, PIPS 2.0, is being designed to include most ice-covered regions in the northern hemisphere. Similar to the PIPS and RPIPS systems, the PIPS 2.0 ice model requires atmospheric and oceanic forcing. NOGAPS, a global model, can provide the necessary atmospheric forcing, but the oceanic forcing used by PIPS and RPIPS does not cover the larger area forecast by PIPS 2.0. To obtain the appropriate oceanic forcing, a diagnostic version of a multilevel (15-level), baroclinic, ocean model (Cox, 1984) was coupled to the ice model (Hibler, 1979 and 1980). The ocean model is initialized from a climatology of temperatures and salinity (Levitus, 1982) and uses a Navy data base for bottom topography. Testing of various coupling techniques was first done on the smaller, less-computer-intensive region covered by PIPS. Results of this coupling showed that using variable oceanic forcing as opposed to an ocean climatology had a serious impact on the accurate prediction of seasonal and year-to-year variability in the ice cover (Riedlinger and Preller, 1991). In particular, the variability in the oceanic heat flux allowed by this coupling was responsible for a large part of the variability in the ice cover.

Once these models were successfully coupled over the region covered by PIPS, the same techniques were applied to the larger area covered by PIPS 2.0. Part of the coupling included conversion of the ice model from cartesian into spherical coordinates to be compatible with the ocean model. Both the ice and ocean models were first tested separately on the PIPS 2.0 grid, which uses $\frac{1}{2}°$ resolution, and then they were coupled. The PIPS 2.0 coupled ice-ocean model is ~30 times larger ($179 \times 179 \times 15$ grid points versus $47 \times 25 \times 15$ grid points) than the PIPS coupled ice-ocean model and uses a smaller timestep, (30 minutes versus 2 hours) in the ocean model. It is necessary to do the testing of this model on a powerful computer. PIPS 2.0 is presently run on the Navy's Cray YMP computer called the Primary Oceanographic Prediction System (POPS) located at the Stennis Space Center in Mississippi. A similar machine will replace the existing operational computer at FNOC in late 1992.

The PIPS 2.0 coupled ice-ocean model is presently being tested using 1986 NOGAPS forcing. Figure 4 shows the March monthly mean ice thickness and ice drift from a 6-year, near-equilibrium, model integration of PIPS 2.0. Again, the thickest ice is found in the central Arctic along the Canadian Archipelago, and the thinnest ice is in the marginal seas. The ice edge agrees with the JIC's ice-concentration analysis in most places, but in a few locations there is too little ice (e.g., the eastern Bering Sea and Hudson Bay). This may be due to inaccuracies in the predominantly wind-driven ice advection in these locations. Ice

The next-generation ice forecasting system . . . to include most ice-covered regions in the northern hemisphere.

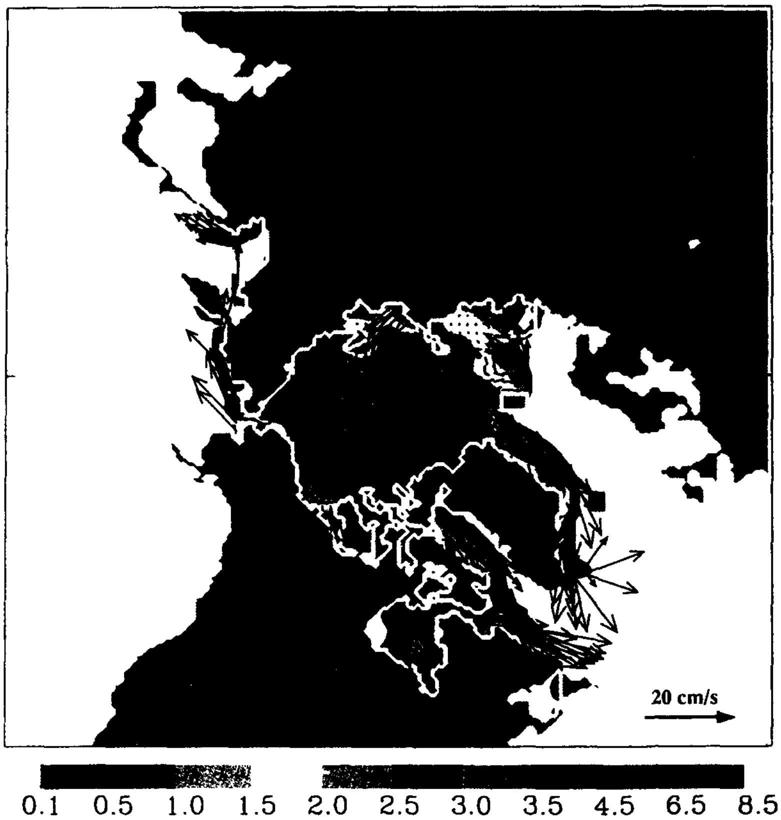


Fig. 4: March 1986 averaged ice thickness and ice drift from the PIPS 2.0 model. Color bar indicates the ice thickness in meters and the scale vector for ice drift is 20 cm/sec.

drift corresponds to the monthly averaged winds from the NOGAPS March 1986 pressure fields, which show a clockwise circulation in the western Arctic and a transpolar drift flowing south through the Fram Strait into the Greenland Sea.

The initial testing of this model has been very promising. Operational testing of the model is scheduled for the 1992–1993 time frame. When it becomes operational, this model will serve as an upgrade for PIPS.

Future plans for the Navy's sea-ice forecasting include the development of additional high-resolution regional models (e.g., the Sea of Okhotsk), the use of near real-time passive microwave data (SSMI) for initialization of the forecast system, and the coupling of atmospheric models to the ice-ocean models.

Acknowledgements

Thanks goes to Ms. Shelley Riedlinger for plotting the figures used in this paper. This project has been funded through the Navy Ocean Modeling and Prediction (NOMP) Program by the Office of Naval Technology (program element 62435N) and by the U.S. Space and Naval Warfare Systems Command (program element 63207N). This paper, NOARL contribution 322: 068:91, is approved for public release; distribution unlimited.

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FEATURE

OPERATIONAL MODELING: SEMIENCLOSED BASIN MODELING AT THE NAVAL OCEANOGRAPHIC OFFICE

By C. Horton, M. Clifford,
D. Cole, J. Schmitz
and L. Kantha

THE U.S. Naval Oceanographic Office (NAVOCEANO) is developing an operational capability to forecast ocean currents and thermal structure in nearshore regions and semienclosed seas. Development thus far has emphasized semienclosed seas because of the relative ease of defining boundary conditions. The first area for which a modeling system was implemented was the Persian Gulf. Operational use of the modeling system for this area began in November 1990, but the modeling system has continued to evolve and undergo additional testing. We have applied the modeling system developed for the Persian Gulf to two other semienclosed basins, the Red Sea and the Mediterranean, and they are being tested for possible operational use.

Principal elements of the modeling system are: 1) a three-dimensional, primitive-equation circulation model developed originally at Princeton University (Blumberg and Mellor, 1987), 2) temperature, salinity, and bathymetry data bases, and 3) the NORAPS (Navy Operational Regional Atmospheric Prediction System) meteorological forecasts for the Persian Gulf area from the Fleet Numerical Oceanography Center. We also employ a graphics-display and verification software package provided by the Institute for Naval Oceanography (INO) to display our model results. The circulation model was developed originally at Princeton University and Dynalysis of Princeton by G. Mellor, A. Blumberg, H. Herring, L. Kantha, and others. The version of the model we use was optimized at INO to run on a Cray supercomputer. Important characteristics of this model are that it has complete thermodynamics and includes imbedded turbulent-closure submodels, which provide Ekman surface and bottom layers.

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The model uses terrain-following vertical coordinates, where each level is a fixed fraction of the water depth. Depending on the basin being modeled, between 14 and 22 levels have been used. In all cases the spacing of the levels is reduced near the surface and bottom so that the top and bottom boundary layers are resolved. The present version of the Persian Gulf model uses an along-axis resolution of 8.4 km and a cross-axis resolution of 7.4 km. The Red Sea model uses along-axis and cross-axis resolutions of 14 and 6 km, respectively. The resolution of the Mediterranean version of the model is 10 km in both directions.

All model versions are forced with NORAPS meteorological forecasts. NORAPS provides analyzed meteorological fields at 12-hour intervals and forecast fields 48 hours ahead at 6-hour intervals. The fields we use are near-surface winds, air temperatures, and vapor pressures (equivalent to specific humidity). From these fields we derive the surface wind stress and the air-sea heat and salinity fluxes. In doing this we ignore precipitation and assume a fixed cloud fraction, although we plan eventually to use forecast precipitation rates and to estimate cloud fraction automatically from infrared imagery. We also record surface atmospheric pressure and are testing this term as additional forcing for the model.

Running the model requires bathymetry and initial-temperature and salinity fields. The bathymetry we use originates as a ?-minute resolution field that we smooth to model resolution. When starting the model from rest, we use gridded temperature and salinity fields derived from the Master Oceanographic Observation Data Set, which is a collection of ungridded temperature and salinity profiles from many sources. The gridded temperature and salinity fields were constructed with a horizontal resolution of 20 minutes and then interpolated to model resolution. A temperature field was constructed for each season. In the Persian Gulf, because of a paucity of data,

The first area for which a modeling system was implemented was the Persian Gulf.

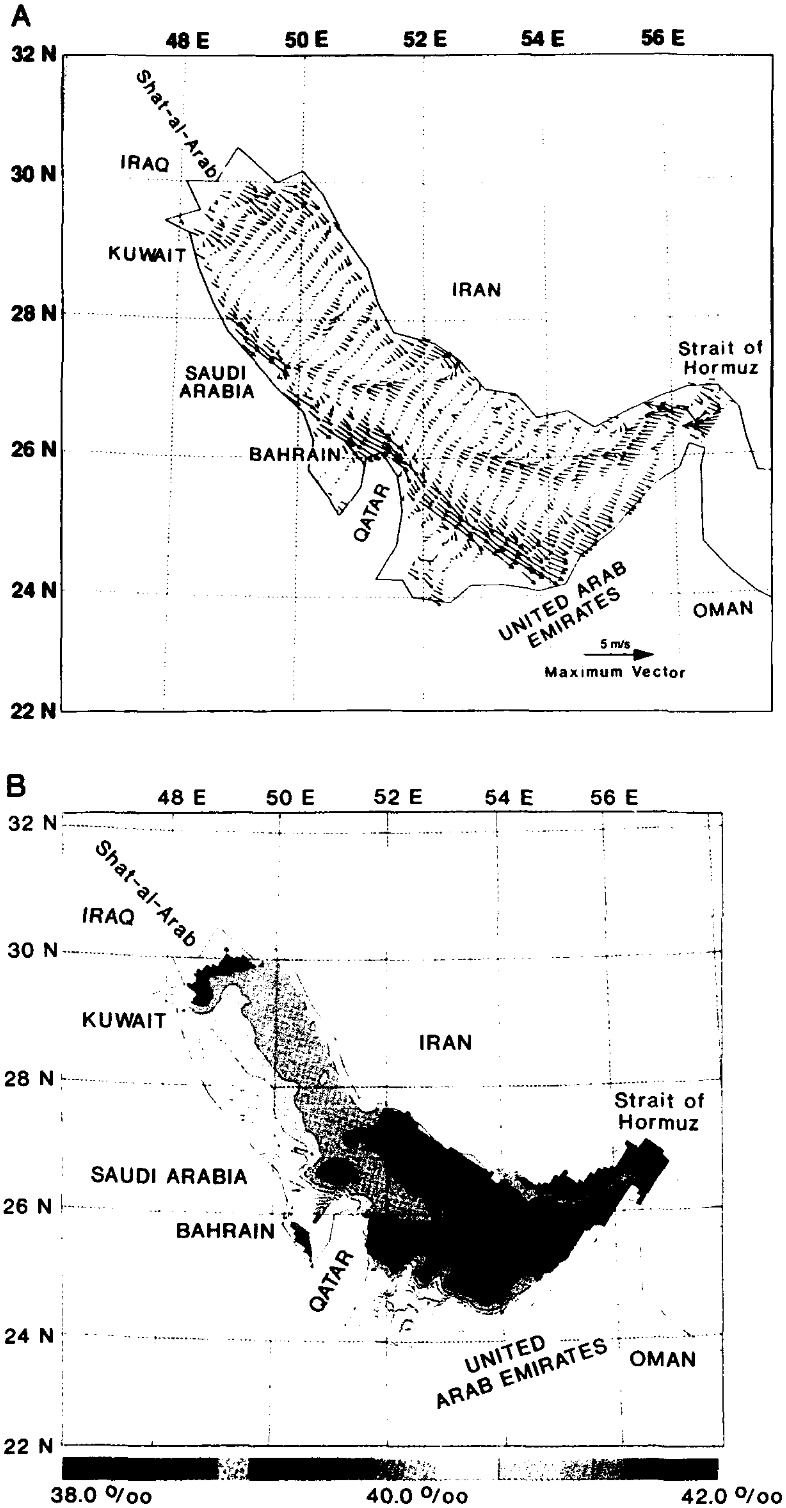

*Fig. 1: (**A**) Predicted surface velocity for the Persian Gulf after 90 days using climatological winds and heat fluxes. (**B**) Predicted near-bottom salinity for the Persian Gulf after 90 days using climatological winds and heat fluxes.*

only an annual-average salinity file was made. At the end of each model run, the temperature, salinity, and velocity fields necessary to initialize the next model run can be saved. Most operational forecasts are initialized in this manner.

Model Predictions

The Persian Gulf is a shallow, semienclosed basin with a mean depth of only 25–40 m. The circulation of this basin is primarily driven by the local wind stress and secondarily by thermohaline forcing. The prevailing wind in the Persian Gulf is from the northwest and is called a shamal. A monthly climatic atlas shows winds generally down the axis of the Persian Gulf (Meteorological Office, 1949). Mean scalar wind speeds in the center of the Gulf are typically 14 to 22 m/s. A wind-driven generally cyclonic circulation results. However, especially in the winter, the shamal can be interrupted by winds from varying directions. For example, winter storms are preceded by south winds that veer to northwest after the storm passage. This can temporarily reverse the surface circulation. The lands surrounding the Persian Gulf are dry so there is strong excess evaporation over the Persian Gulf. This results in a Mediterranean-style thermohaline circulation (Brewer and Dryssen, 1985). Accordingly, at the Strait of Hormuz in our model there is a surface inflow of relatively fresh (37–37.5 ppt) water and an outflow of deeper, more saline (38–39 ppt) water on the southern side.

We show model results for a single scenario. Using essentially yearly averaged winds, down the axis at 5 m/s, and yearly averaged heat fluxes, we spun up the model for 90 days to nearly steady state. Figure 1A shows the predicted surface velocity. We see the generally cyclonic circulation but with more complexity. Some of the highest current speeds are in the inflow through the southern side of the Strait of Hormuz. The strong inflow along the southern side of the Strait is consistent with a current-speed climatology by Schott (1918). This inflow feeds the eastward coastal current along the south edge of the Gulf, which is strongest near Qatar. Along the Iranian coast, there is another eastward current which terminates at ~51°E, where its remnant turns south into the interior. Figure 1B shows that near-bottom salinities ~40 ppt are predicted in the very shallow coastal areas on both sides of Qatar. The highest value predicted is in the gulf south of Bahrain, where Chandy, *et al.* (1990) reported hypersaline conditions. At the Strait of Hormuz, we see the Mediterranean-style inflow of relatively fresh water and outflow of more saline water, although most of the inflow is near the surface. A source of fresh water is specified to simulate the outflow from the Shat-al-Arab waterway. The limited effect of this source can be seen at the extreme western edge of the Persian Gulf.

Model Verification

The model predicts the three-dimensional evolution of the temperature, salinity, and velocity

fields. However, operational use of the model has been limited to the prediction of near-surface current speeds. As such, testing and evaluation of the modeling system has concentrated on measuring the accuracy of the modeled near-surface velocity fields. To measure this accuracy we have relied on air-deployed, sonobuoy-sized, environmental data buoys that are tracked in near-real-time using System ARGOS. We typically obtain four positions a day per drifter from which we compute the drifter speeds. We study the veracity of our modeling system by comparing predicted and observed drifter speeds. However, modeling the translation of the drifters is not simple because they are subject to substantial wind drag and water drag at more than one depth. We model three main sources of drag: the submerged portions of the instrument housing and flotation bag, the drogue that was usually set at 4-m depth, and wind drag because the ratio of wetted-to-air area for these drifters is only 3.6.

During March 1991, five drifters were deployed in the northwest Persian Gulf. While two of the drifters quickly went ashore, three of the drifters, as shown in Figure 2, provided long tracks suitable for testing as they moved downstream toward Qatar. Forecast and observed drifter tracks were compared during overlapping 3-day periods. Results are shown separately for the three drifters in Figure 3. The curves shown are normalized distance errors, which were derived from least-square polynomial fits to composites of all the data. Normalized errors in the modeled drifter tracks are obtained by dividing the absolute errors by the distance the drifters actually moved. The absolute errors are obtained by computing the distance between the modeled and observed drifters that started at the same position at the beginning of each 3-day period. When the normalized error is less than one, the model is better than persistence because the model error is less than that obtained by assuming no motion. The results from all three drifters decline to ~0.5 after 72 hours. The normalized errors, of course, are much closer to one for very short-term predictions, because there is little net motion of the drifters. There were occasions when the model forecasts gave very large normalized errors. These tended to occur when the winds driving the model incorrectly timed frontal passages. Under these conditions the observed and predicted drifter tracks could, for a while, be opposite in direction.

Future Plans

Upgrading and testing of the modeling system will continue, but the basic configuration of our modeling system for the Persian Gulf is complete. Certainly, we will continue to tune the model to improve our test results. Working with INO, we also hope to improve our ability to display the model outputs to better understand the physics of our forecast fields. However, our modelling system is incomplete in the description of the near-surface physics. The surface boundary-layer submodel only includes Ekman dynamics. Within a distance of the order of the wave height, a zone we are interested in, additional physics needs to be added. Certainly, we need to compute the wave-induced current speeds. We are in the process of implementing a spectral-wave model in the Persian Gulf and other semienclosed basins. By doing this, we hope to compute the sum of the wind- and wave-induced near-surface drifts.

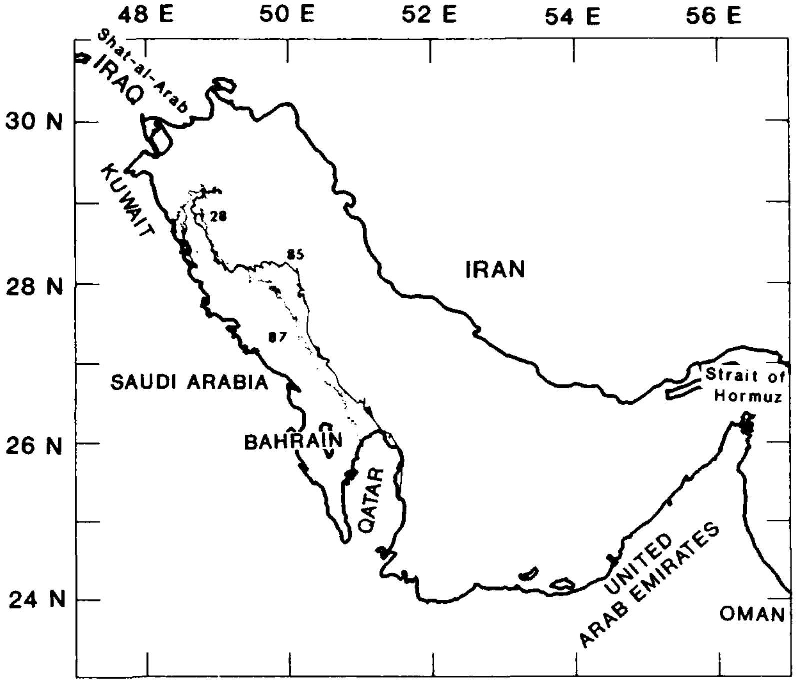

Fig. 2: Drifter tracks used to verify the model.

We study the veracity of our modeling system by comparing predicted and observed drifter speeds.

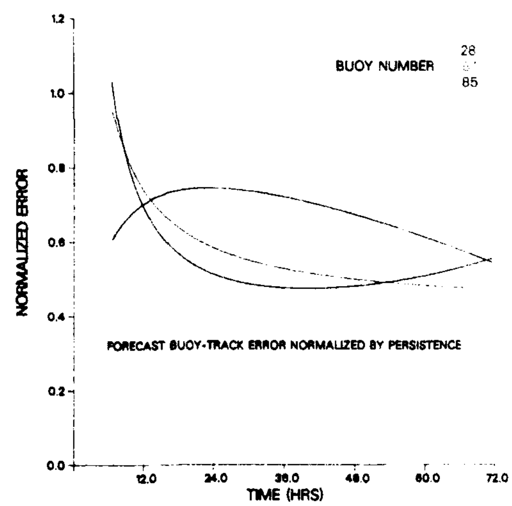

Fig. 3: Forecast errors of drifter tracks normalized by persistence.

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A WESTERN TROPICAL ATLANTIC EXPERIMENT (WESTRAX)

By Wendell S. Brown, William E. Johns, Kevin D. Leaman, Julian P. McCreary, Robert L. Molinari, Phillip L. Richardson and Claus Rooth

RECENTLY, a group of researchers from the U.S. and the broader international community have developed coordinated plans for observational and modeling work in the western tropical Atlantic. The overall research program is referred to as WESTRAX, for Western Tropical Atlantic Experiment. This article summarizes the research plans of the various participants and the scientific issues that have motivated the studies.

Background

Ocean heat flux is a significant component of the global energy balance. Vonder Haar and Oort (1973) found that, on a global average, the oceans between the equator and $\sim 30°N$ transport more than half the heat required to balance the energy loss at more poleward latitudes. At subtropical latitudes in the North Atlantic (where the ocean heat flux is a maximum), western boundary currents represent an important component in the global heat budget (Bryden and Hall, 1980). Global-scale thermohaline circulation is believed to play a central role in the net northward interhemispheric transport of mass and heat in the Atlantic Ocean (Broecker *et al.*, 1985; Atlantic Climate Change Working Group, 1990). The notion of a global thermohaline "conveyor belt" involves warm upper-ocean transport from the Indian and Pacific Oceans moving northward through the Atlantic and a southward return of colder deep flow from the subpolar regions in the North Atlantic.

Important components of the global thermohaline conveyor belt are seen in the tropical Atlantic. The cross-equatorial transport of upper tropical Atlantic waters is comparable with the total rate of equatorial upwelling driven by the tropical wind systems. Thus, it appears that the deep and shallow parts of this meridional overturning system may be linked in the tropics. There is reason to believe that an improved understanding of these so-called conveyor-belt dynamics will help explain observed correlations between African and Brazilian drought cycles and ocean surface-temperature asymmetries in the Atlantic. It is hypothesized that changes in the meridional overturning rate induce climatically important changes in the surface ocean temperature anomalies.

Important components of the global thermohaline conveyor belt are seen in the tropical Atlantic.

What is the role of the tropical Atlantic in the northward interhemispheric heat transport in the Atlantic basin? To answer this question, it will be important to determine how much water is transported across the equator at different depths within the western-boundary current system and what fraction of this water is carried poleward into the subtropical basins of the North and South Atlantic. Answering this question requires a more complete understanding of the structure of western-boundary currents in the tropical Atlantic and their coupling to the interior circulation. A growing body of observations suggests that, at the surface, the northern-hemisphere summer and fall circulation in the western tropical Atlantic is dominated by the retroflection of an intense western-boundary current known as the north Brazil current (NBC). During this time, the upper layer of the NBC, which transports from 30 to 50 Sverdrups, feeds the north equatorial countercurrent (NECC). The lower layers of the NBC within and just below the thermocline also retroflect (Metcalf and Stalcup, 1967), but apparently at different locations, to feed the equatorial undercurrent and the subsurface branches of the NECC—more permanent features of the circulation. This layered structure of the NBC appears to be connected in some way to the presence of two quasipermanent eddies adjacent to the western boundary near 4°N and 8°N, commonly referred to as the Amazon and Demerara Eddies, respectively. These complex upper-level currents and underlying flows of

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Antarctic intermediate water, Antarctic bottom water, and North Atlantic deep water are believed to play a central role in the net northward heat transport in the Atlantic.

Several of the earliest observational programs [such as the Equatorial Atlantic Program (EQUALANT), 1963–1964] addressed some of these questions concerning variability in the interior tropical oceans. The Atlantic Tropical Experiment (summer and fall 1974) of the Global Atmospheric Research Program marked the beginning of modern intensive studies of tropical ocean dynamics in the Atlantic. Studies on the response of the tropical Atlantic to transient wind forcing ensued. Notable efforts include the Seasonal Response of the Equatorial Atlantic (SEQUAL) and the Français Ocean et Climat dans l'Atlantique Equatorial (FOCAL) complementary U.S. and French observational programs, during 1983–1984. In addition, the National Oceanic and Atmospheric Administration (NOAA), together with the Geophysical Fluid Dynamics Laboratory, developed a detailed numerical model for the basin-wide dynamic response to observed winds. Spanning this whole period has been the development of analytical and simplified numerical models aimed at understanding the physics of the wind-forced variability in the equatorial ocean on seasonal to interannual time scales. These efforts have contributed significantly to the development of models for El Nino dynamics in the Pacific.

These complex upper-level currents and underlying flows . . . play a central role in the net northward heat transport in the Atlantic.

The relatively few observations that have been made in the western tropical Atlantic have been used primarily to describe its large annual signal. Hydrography indicates that the most intense circulation and largest transports occur during the northern-hemisphere summer when the NBC retroflects and feeds the NECC (Fig. 1). The least-intense circulation and smallest transports occur during the northern-hemisphere winter when a significant portion of the NBC is believed to continue along the South American coast into the Caribbean (Johns and Molinari, 1989). A quantitative description is not yet available of the annual cycle for the upper ocean transport of either the NBC or the Amazon and Demerara Eddies, around which the NBC retroflects at times. In fact, recently analyzed satellite images of ocean-surface color (Muller-Karger *et al.*, 1988) suggest that the Demerara Eddy is not even a steady feature. The work of Johns *et al.* (1990) suggests that the NBC retroflection sheds eddies, which move northwestward along the South American coast. At thermocline and subthermocline depths, indirect evidence indicates an annual modulation in the intensity of the Amazon Eddy and the subsurface branch of the NECC just to the east. The relationships between the boundary flows, eddies, and zonal currents remain essentially undefined, however.

Models ranging in dynamical complexity from simple analytical models (Csanady, 1985; Weisberg and Tang, 1985) to comprehensive general circulation models (GCMs) have been applied to the region. The numerical modeling studies of Philander and Pacanowski (1986) suggest that the surface currents of the western tropical Atlantic play an important role in ocean heat flux in the region. In particular, when the model NBC retroflects in the summer, northward heat flux is a

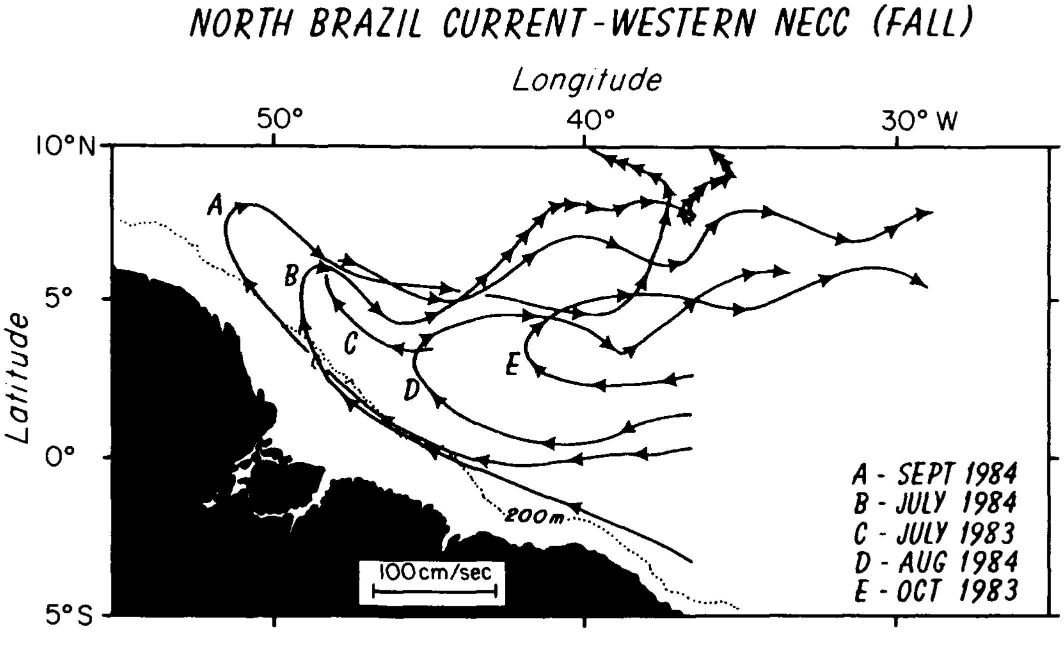

Fig. 1: Float tracks demonstrating the retroflection of the NBC (after Richardson and Reverdin, 1986).

minimum across 8°N. When the model NBC is continuous along the coast, northward heat flux is a maximum. Thus, the western tropical Atlantic Ocean appears to be a critical location for monitoring the net northward heat (and fresh-water) fluxes in the Atlantic basin. Several other numerical models have been applied to the region for somewhat different purposes (Schott and Böning, 1991; Thompson, McCreary, personal communications). All of these model results show an undercurrent flowing southward along the slope to join with either the equatorial undercurrent (EUC) or a subsurface branch of the NECC, depending on season. Although this flow has been detected in hydrographic sections, it has not been observed directly. Clearly, models will continue to play an essential role in estimating heat and mass transports and suggesting strategies for observing this complex region.

The observational and modeling studies of the western tropical Atlantic to date raise a host of important scientific questions concerning the dynamics of the various current components concentrated along the western boundary. In particular, it is unclear why the thermocline and subthermocline currents separate from the western boundary at different latitudes to feed the various zonal flows. Are separation latitudes dictated primarily by the structure of the wind-forced flow regime in the central basin or do local boundary-current dynamics prevail? What forces the subsurface currents? What is the dynamical role for the NW-SE orientation of the South American coastline?

Other dynamical questions concern the role of the western tropical Atlantic in the dynamics of the thermohaline circulation of the Atlantic region. In particular, do the western tropics have a significant dynamic role in controlling the intensity of the meridional overturning cell in the Atlantic basin? There are also key questions concerning the deep-circulation components. In particular, do deep recirculation gyres, like those observed south of the Gulf Stream, exist in this region? If so, what is the offshore transport of the deep western-boundary current? What is the relationship between the thermohaline and eddy-driven transports? How is the deep eddy field related to the near-surface circulation field? What is the temporal variability of the deep circulation?

Many of these scientific issues are being addressed by WESTRAX.

The WESTRAX Study

One of the long-term goals of physical oceanographic research in the western tropical Atlantic is to estimate the cross-equatorial transport of water and heat. In order to detect long-term changes in the meridional mass and heat transport of the tropical Atlantic, a much better understanding of the seasonal variability in the current and property structure of the region must be obtained. Toward that end, an international group of scientists (Table 1) is cooperating in the context of WESTRAX to determine the first-order kinematics and dynamics of the flow in the western tropical Atlantic. During 1990 and 1991, the WESTRAX field program has obtained data that will be used to describe the annual cycle in the large-scale structure of the velocity and hydrographic properties over the full water column in the western tropical Atlantic Ocean between the equator and 15°N. Subsequently, the field data and model results will be compared in order to better understand the physics of the regional circulation in the broader context of Atlantic-basin thermohaline circulation.

One of the long-term goals . . . to estimate the cross-equatorial transport of water and heat.

Scientific Objectives

The specific objectives of the WESTRAX studies are as follows:

1. to describe the annual evolution of the three-dimensional velocity field for the NBC, Guiana current, and the western parts of the NECC, south equatorial current, and EUC;
2. to determine the seasonal changes in the transport connecting the different components of the upper-level current system in the western tropical Atlantic;
3. to measure the temporal changes in the structure and transport of the intermediate and deep western-boundary currents in the region;
4. to determine the basic physical mechanism controlling the evolution of the NBC retroflection and associated eddy dynamics in the region; and
5. to estimate the proportion of the net meridional transport contained in the western boundary current system.

Experimental Plan

Observations. The WESTRAX observations include: ship surveys with Conductivity Temperature Depth and Oxygen probe (CTD/O_2), Expendable Bathythermograph (XBT), and Acoustic Doppler Current Profiler (ADCP) measurements;

Table 1
WESTRAX activities and associated principle investigators.

NOAA/NSF Large-Scale Ship Surveys, Pegasus/Doppler Velocity, CTD/XBT/O_2/Nutrient— W. Brown (UNH), E. Johns (NOAA), K. Leaman (RSMAS), R. Molinari (NOAA), D. Wilson (NOAA).
RSMAS Moored Currents—W. Johns, T. Lee
Kiel Modeling, Pegasus Velocity, CTD Ship Surveys, Moored Currents—F. Shott
Lamont Moored Inverted Echo Sounders—E. Katz
ORSTOM Small-Scale Ship Surveys, Moored Currents— C. Colin
Wood's Hole Oceanographic Institute Floats— P. Richardson, W. Schmitz
Maryland Modeling—J. Carton
Nova Modeling—J. McCreary, P. Kundu, P. Lu
NOARL Modeling—D. Thompson, J. Kindle, H. Hurlburt

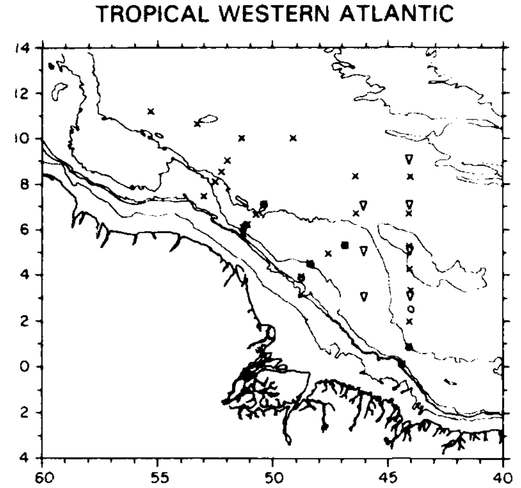

Fig. 2: The WESTRAX moored array. The Pegasus-profiling (X), current-meter (open circles), and inverted-echo-sounder (inverted triangles) stations are indicated.

and moored arrays consisting of current meters, inverted echo sounders, and acoustic transponders for repeated shipboard Pegasus velocity profiling (Fig. 2). Deployments of deep floats and a few surface drifters augment the other observations. The 1990–1991 schedule of WESTRAX activities is presented in Fig. 3.

There were five large-scale shipboard surveys of Pegasus and Doppler absolute velocity and hydrography supported by NOAA and NSF (National Science Foundation) (Fig. 2). These surveys were timed to sample the regional current system during different phases in the annual cycle of the near-surface NBC. A comparison of the January 1990 and 1991 survey results will make possible the estimate of interannual changes in the system. The French at the Office de la Recherche Scientifique et Technique d'Outre-Mer (ORSTOM) conducted a series of Pegasus and CTD measurements along a transect from the coast of French Guiana to the nominal center of the Demerara Eddy.

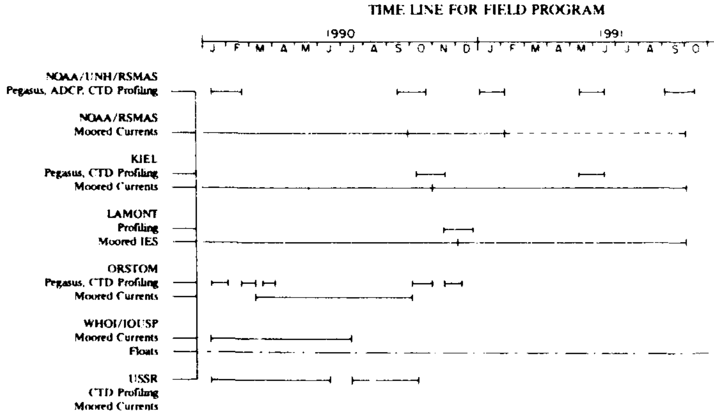

Fig. 3: The WESTRAX timetable of field-program activities.

The elements of the moored array were located so as to monitor the variability of the NBC, equatorial, and deep western-boundary current systems at several key locations. The Kiel current-meter moorings spanned the NBC along 44°W near the equator (see Fig. 2). The University of Miami (RSMAS; Rosenstiel School of Marine and Atmospheric Sciences) moored current-meter array spanned the NBC at ~5°N between the Amazon and Demerara Eddies. The short-term ORSTOM current-meter array spanned the NBC at ~7°N. The Lamont inverted echo sounders (IES) were used to monitor the dynamic height field and associated geostrophic transport associated with flow into and out of the NBC retroflection region.

In an effort to measure the cross-equatorial transport of subsurface water, Woods Hole Oceanographic Institute (WHOI) launched 44 Sofar floats and 4 Bobbers in early 1989 distributed at depths of 800, 1,800, and 3,500 m. Most of the floats were deployed in the western boundary current at ~6°N between French Guiana and Brazil, some along the equator, and some along 11°N. A pair of surface drifters—deployed in the region of the NBC retroflection in November 1990—provided Lagrangian current information in the region until mid-February 1991.

Modeling. Nova University modelers are using a $2\frac{1}{2}$-layer model (a 3-layer model with an inert lowest layer) to study regional dynamics. The relatively simple model contains many of the essential dynamical processes believed to be important in the WESTRAX region: a subsurface layer for the development of undercurrents, nonlinearities that allow for unstable currents, a parameterization of upwelling and entrainment, and thermodynamics in both layers. The model is being forced with realistic winds, and the resulting solutions are being compared with observations. To investigate the fundamental dynamics, a variety of dynamically simpler solutions are being obtained and contrasted. Naval Oceanographic and Atmospheric Research Laboratory (NOARL) modelers are developing a hierarchy of primitive-equation layer models in both global and regional basins with resolutions varying from eddy-resolving to rather coarse grids. Of relevance to WESTRAX is their interest in understanding the dynamics responsible for the 26- and 50-day oscillations observed in the equatorial Atlantic (Johns *et al.*, 1990). Kiel University modelers are comparing different solutions to a multilevel GCM with one another and with observations. University of Maryland modelers are conducting modeling and assimilation studies of the tropical Atlantic Ocean using primitive equation models to define the mechanisms controlling seasonal storage and transport of heat, momentum, and salt.

Relation to other programs. WESTRAX benefits from other ongoing programs in the region. For example, the Tropical Ocean and Global Atmosphere Progran. (TOGA) supports some of the Lamont IES (E. Katz) and XBT ship-of-opportunity (R. Houghton) observations pertinent to WESTRAX objectives. The NSF-supported AmasSeds project (A Multidisciplinary Amazon Shelf SEDiment Study) in the region of the Amazon outflow includes a physical oceanographic component (R. Beardsley, WHOI; B. Castro, Instituto Oceanográfico, Universidade de São Paulo [IOUSP]) on the landward side of the WESTRAX region. Collaboration is also anticipated with the Soviets, who conducted three extensive hydrographic and current surveys of the region in 1990.

Although the observational phase of WESTRAX has ended, the WESTRAX Pegasus transponders should be useful through September 1992. The community is encouraged to take advantage of that opportunity to make further measurements, as well as to engage in other relevant collaborations with WESTRAX investigators.

Acknowledgements

In addition to the contributions of the authors, this description benefitted from discussions among the other participants in the January 1990 and February 1991 Miami WESTRAX workshops. W. Brown's effort was supported by the National Science Foundation under grant OCE 8912260.

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PRESIDENT'S REPORT

By D. James Baker

THE U.S. NAVY OCEAN MODELING and Prediction Program, a focus for this issue of *Oceanography*, is a central element of Navy operations that has important implications for the broad international community interested in environmental assessment, monitoring, and prediction. The Navy has played a key role in the development of ocean sciences research and facilities in the United States and in applying research to improve ocean understanding and predictions. The U.S. Department of Defense is being cut back in funding as the nation reorders its priorities. It is important both to recognize the Navy's role and to look toward the future challenges for the community that will require the help of the Navy.

Without the many far-seeing individuals in the Navy who interacted closely with the academic community in the late 1940s and early 1950s, ocean science in the United States would be far different and far less healthy than it is today. For example, the decision of the Navy to provide ships to the academic community after World War II set the tone for U.S. academic oceanography, a mode of distributed ship operations that has proven remarkably effective over the long haul. The Navy guided oceanography through the decades after the war from a relatively small, regionally based science to the global programs that we have today.

In recent years, other agencies have joined the Navy in ocean interests so that today we have a partnership of agencies supporting ocean research. The Navy continues to play a central role in this partnership. Today, there is a dedicated set of individuals at the Office of Naval Research, the Office of the Oceanographer of the Navy, the Naval Oceanographic and Atmospheric Research Laboratory, and in other parts of the Navy who help guide our field. As is evident from the articles in this issue, the Navy has a global scope in modeling and prediction as well as in observations. The results from the Navy program are providing useful and important operational results, and the techniques being developed will be used in the broader context of environmental prediction.

As the nation looks toward the future, pollution and global change dominate the environmental agenda. Our environment is being threatened by a variety of factors: increasing population puts increased stress on all aspects of the ocean, most noticeably in the coastal region, but also on the global ocean as waste disposal becomes more and more difficult. Increased pressure on fisheries leads to fleets operating globally and to the disappearance of formerly stable ecosystems. Increasing concentrations of greenhouse gases may be leading to global warming; clearly the ocean as the flywheel of the climate system must be understood and monitored as part of any environmental system. The Navy programs will contribute to better understanding of all of these issues.

There is international agreement for the need to expand the infrastructure we now have in place for monitoring, assessing, and predicting change in our environment. The expansion will build on national programs such as the ones discussed in this issue, on global research programs, and existing observational systems such as the World Weather Watch, the Integrated Global Ocean Station System, the Global Investigations of Pollution in the Marine Environment, and other such systems. Eventually, we can look to the establishment of a global-ocean observing system that will provide the infrastructure to obtain information from coastal and mid-ocean regions. This information will address issues related to changes in regional and global environments at all time scales.

A global-ocean observing system will provide systematic, long-term observations on the physical and chemical state of the ocean and on the state of ecosystems in the ocean; it will improve our ability to develop models and make prediction of changes in the ocean and associated ecosystems; it will improve our understanding and assessment of biogeochemical cycles; it will improve our ability to assess the effects of global change at regional scales on intensively exploited ocean regions; and it will provide data for the assessment of the health for the marine environment and its resources. This is the challenge of the future: to establish a fully effective global system for monitoring the ocean and providing operational ocean predictions. Henry Stommel perhaps put it best when he said, "Today, in a time of concern over the possibility of potentially disastrous changes in climate, the nation or nations that establish a world-ocean observing system would make a splendid contribution to the world."

The scope of a global-ocean observing system is international, and thus many nations will be involved, both developed and developing. Outside the United States, individual nations such as France, Germany, Japan, and the United Kingdom have all supported technological advances for global observations of the ocean. International organizations also will be involved, for example, the European Commission has supported a project EUROMAR for the development of new technology for ocean monitoring. This was done under the general umbrella of their EUREKA organization, which is intended to coordinate the development of advanced technology throughout Europe. The expertise and resources of international organizations such as the Intergovernmental Oceanographic Commission, the World Meteorological Organization, the United Nations Environment Program, and the International Maritime Organization will be essential to the success of the system.

But in the end, it will be national contributions that make the global-ocean observing system work, just as national contributions are key to the success of the World Weather Watch. The Navy, with its global interests and achievements in ocean modeling and prediction, has played and will play a major role in the development of the global-ocean observing system. The U.S. Navy's global reach and expertise in operating such a system will key to the success of the system in the United States. The Navy Ocean Modeling and Prediction Program sets a standard for other agencies to strive towards as the nation prepares to meet this new challenge. However, with the cuts in the funding for the Department of Defense, these efforts are endangered. Your support of the Navy is now needed more than ever. Write to your elected officials and make sure that they are aware of these programs and their important contributions to the national interest in the environment. ❑

ELECTION RESULTS

A final note from D. James Baker:

It has been my pleasure to serve as President of the Society in its first years. I have long believed that oceanographers need an active and effective professional society; we now have a very good start in that direction. I'm looking forward to becoming the Society's first Past President and turning over the gavel to Arnold Gordon as President and Margaret Leinen as President-Elect. I wish them both the best of success in their terms.

The new council members are: President-elect, Margaret Leinen, University of Rhode Island; Physical Oceanography Counselor, Tommy D. Dickey, University of Southern California; Biological Oceanography Counselor, Richard T. Barber, Duke University.

SPECIAL OFFER TO MEMBERS OF THE OCEANOGRAPHY SOCIETY

The Society has concluded an agreement with Pergamon Press to allow its members to purchase subscriptions of the following journals at special reduced rates.

Continental Shelf Research	US$55.
Deep-Sea Research Parts A & B	US$95.
Progress in Oceanography	US$55.

The above rates apply for 1992. To take advantage of this offer please send payment with order to: P A HENN at Pergamon Press, Inc., 660 White Plains Road, Tarrytown, NY, 10591-5153, USA (for members in the USA and Canada) or Pergamon Press Plc, Headington Hill Hall, Oxford, OX3 0BW, England, UK (for those in the rest of the world) Free sample copies of any of the above journals are available upon request from Pergamon.

SPONSORED BY TOS

1993 Third Meeting of The Oceanography Society

Seattle will be the site for our third meeting during 13–16 April 1993. Information regarding the meeting will be presented in later issues of *Oceanography*. Please contact TOS headquarters, if you have questions: 1701 K Street NW, Suite 300, Washington, DC 20006-1509.

CO-SPONSORED BY TOS

PACON 92 in Kona, Hawaii

The Fifth Pacific Congress on Marine Science and Technology will be held 1–5 June 1992. A theme of interest to TOS membership is "Post-Baccalaureate Education in Marine Affairs." Requests for information should be addressed to PACON, PO Box 11568, Honolulu, HI 9 828.

1st Thematic Conference on Remote Sensing for Marine and Coastal Environments, in New Orleans

This meeting is sponsored by the Environmental Research Institute of Michigan and is planned for 15–17 June 1992. The contact person is Dr. Robert H. Rogers, ERIM, P.O. Box 134001, Ann Arbor, MI, 48113-4001, USA.

Pacific Ocean Remote Sensing Conference, Okinawa

PORSEC will be held 25–30 August 1992 in the Okinawa Convention Center. More information can be obtained from: PORSEC Secretariat, PO Box 10 Shimuzu, Shizouka, 424 Japan.

6th Annual Workshop on Laboratory Modeling of Dynamic Processes in the Ocean, St. Petersburg, Russia

During 8–12 September 1992, a session will be held on meso- and microstructure of the ocean, including discussions of measurements and models of processes. Please contact Prof. Ju. D. Chashechkin, Institute for Problems in Mechanics, Prospect Vernadskogo 101, Moscow, 17526, CIS.

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